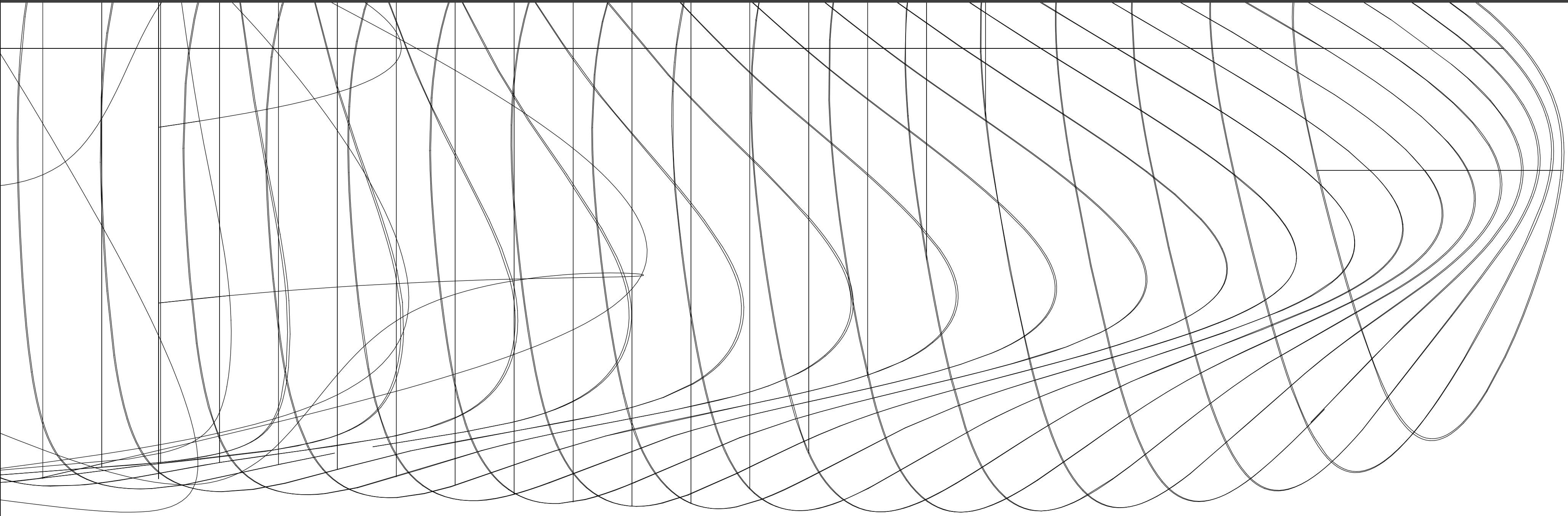

MomusDesign

BENCHTOP CNC ROUTER PLANS

Version 1.2

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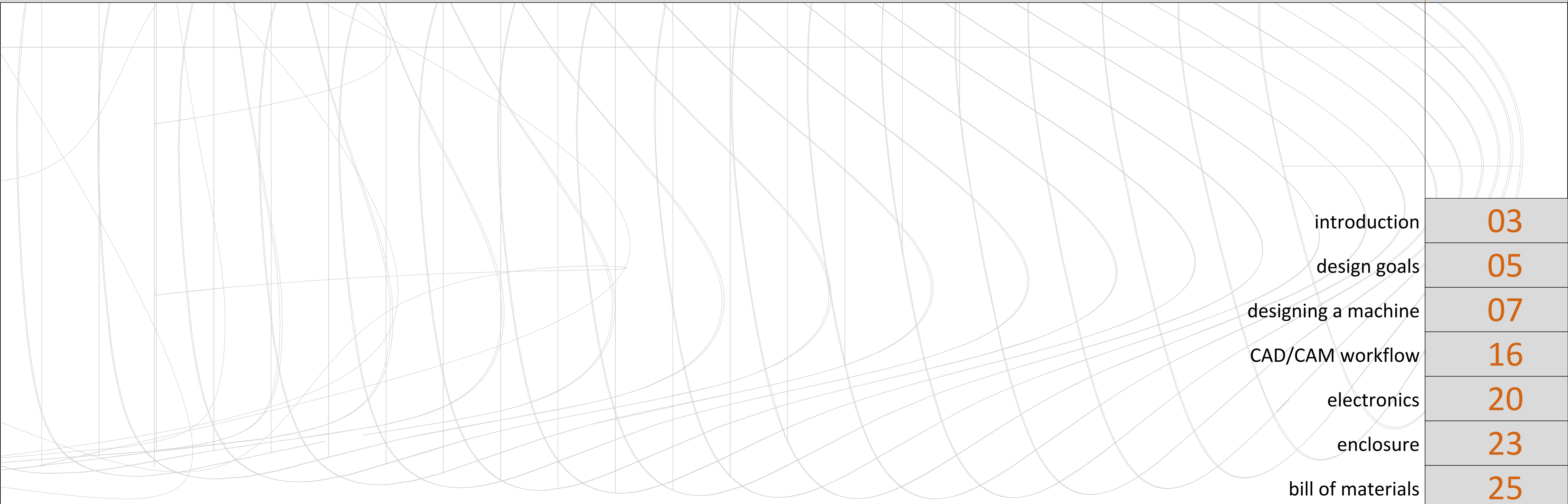

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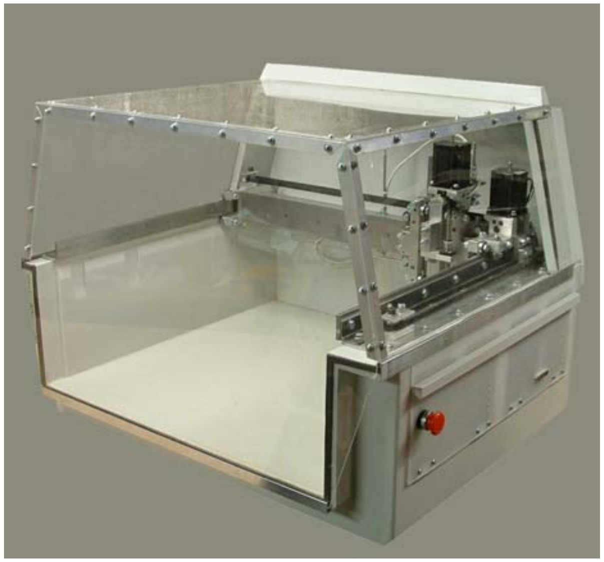

Disclaimer:

The author of this design is not an engineer. This manual outlines the construction of a hobbiest machine designed and built by a hobbiest.

Also note that CNC equipment can be dangerous machinery. In addition to the dangers inherent in operating any power tool, doing so remotely, via computer, adds another level of potential danger. Errors in programming machine movement can have catastrophic consequences.

It is the responsibility of the reader to use the information presented in this manual in a manner deemed appropriate to personal judgement and safety.

Introduction

The machine plans contained in this book bear one significant difference from most others that you will find available. The difference is that these plans were not put together with the goal of selling plans. They are the by-product of building a machine that came into existence because I needed a functional tool. I often see plans advertised for machines that appear to never have even been built, and exist only as computer renderings. While that is great for them, they are making money selling you plans, it isn't so great if you are looking to build a serious machine that can actually be used to cut parts. By contrast, the CNC router that you will see in these pages has seen many, many hours of reliable use, and currently exists in the state that all wood-working machines should be- covered in sawdust.

I designed and built this machine due to an actual need. I am an architect and university professor by profession, and am currently a graduate student working on architectural research. My focus is on digital design processes and construction automation, which involves a lot of model building that requires CNC tools. While I have access to large format CNC equipment at my university, it quickly became apparent that it would be much more convenient to have one in my home workshop.

As my workshop is small (I live in an apartment), and I'm currently a student, this put some serious constraints on cost, space requirements, equipment needed to build it, and keeping any mess relatively contained. So I set about designing a small benchtop CNC router that would suit my needs. I started out by doing the obvious: looking at a whole bunch of home-built machines on the internet. My initial thought was to simply find the best type of machine currently in use, and build a copy of that. Unfortunately I couldn't find one that seemed like it would suit my needs. Most machines that would have been within my budget were these crude contraptions built of MDF and lengths of pipe. So I began to design my own. Well, that ended up taking several years, but I think I have arrived at a design that takes both the performance and sophistication of home-built machines to an new level, while still keeping costs low.

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The personal CNC world

I'm guessing that most of you who have purchased these plans already have some idea of what CNC (Computer Numeric Control) is all about. However, here is a brief overview as a way of further introduction to the particular machine that is covered in this manual. In a nutshell, CNC is a method of using a numerical code to control a machine. Nearly any type of machine or configuration can be controlled this way. If it has a range of movement, whether linear or rotary, it can be controlled by a numerical code that instructs its movements. So CNC can be used for milling machines, lathes, plasma cutters, water jets, hot wire foam cutters, wire EDM, etc. In our case we will be controlling a 3 axis wood router.

Once upon a time, the numbers that were used to control a machine were hand coded and punched into a paper roll that was fed through a reader. The punched holes translated to discrete movement steps. While this is pretty simple when making straight cuts, things get a lot more complicated when attempting curves or freeform shapes. In effect, with these complex shapes, the smaller the distance between the motion steps, the smoother the results. With the advent of the computer, came the ability to generate much more complex numerical code. Furthermore, software can interpolate the movement between the individual steps to result in very smooth machine motions.

More recently there has been a tremendous growth in Do-It-Yourself (DIY) homebuilt CNC equipment. It is now relatively easy to generate the code (typically something called G-Code) to control a machine tool on a home PC (I'm using the term generically, there is Mac based software available as well) and output the signal through a parallel port or USB port to motion control motors. Depending on how complex and sophisticated your needs are, this can even be accomplished with free software.

The implications for this revolution in "personal CNC" are huge. To have the power to create extremely complex parts in a home shop opens up a world of possibilities. It also brings up an important question to consider, and that is whether you really need a CNC controlled router at all. This might be an odd question for someone selling machine plans to be asking, but it needs to be said. In general, if you intend to make parts that can adequately be made by more traditional methods, it is often overkill to be using a computer controlled machine. It may even take considerably longer than traditional methods, when you consider the time necessary to draw/model the part, generate toolpaths, and set up the job on the machine. On the other hand, if you need to create pieces with a higher level of accuracy than you could accomplish otherwise, or want to accurately cut complex geometries, then this is definitely for you. Another group of builders should be mentioned as well, and these are the people who are interested in building a machine just for the sake of building a machine. This is a totally legitimate reason, and was admittedly one factor in my own CNC beginnings. But, if what you are primarily after is a proof of concept, and merely building something just to experience the thrill of controlling it remotely by a computer (and that thrill is very addicitve!), please bear in mind the complexity of this particular machine. This was designed to be a serious tool and as such it is definitely more complex to build than some other designs, which may suit your needs better. So I ask of you that you be honest with yourself in what you need and hope to get out of building a machine, and this one in particular. In return I'll do my best to be as honest and forthcoming as possible in representing what is involved, and the pros and cons of my design.

So, without further introduction let me introduce my machine and the thought process involved in its design.

Machine Design goals

When I started designing my own machine, I listed an initial set of design goals. They read something like this:

Cost: As cheap as possible while accomplishing everything below! My build budget was $300-400 for the machine (excluding motors and electronics).

Tools: It had to be able to be constructed with minimal tools and equipment. It had to be built with tools that most likely would not have a high level of accuracy in themselves. This would require some creative build techniques to end up with something that was more accurate than the tools used to build it.

Accuracy: It needed to be able to cut to a tolerance of about .005". More wouldn’t really be necessary as I would primarily be cutting wood with it, which is not the most dimensionally stable material. It seemed silly to build something to cut to .001" when the material would potentially change size by .030" with a seasonal change in humidity. However, it did need to be far more accurate than I could cut parts by hand, as many of the things I build require them to be assembled from many individually cut parts. This requires much more accuracy than simply carving or engraving a single piece.

Enclosed: Since I live in an apartment it is crucial that my machine have a full enclosure, both for dust control and noise reduction.

Speed: The 20-30 inches per minute that I was seeing in existing homebuilt designs just wouldn’t be adequate. Many of the parts I would be cutting would literally take days at that speed. I needed motion that was closer to 150 ipm.

Alignment: Most of the existing homebuilt machines I was seeing seemed to have serious issues in getting them set up and aligned. Many people were spending more time tying to get their machines into alignment and removing play from the bearings than they had spent building it.

Bind free: This goes hand in hand with the alignment issue. With most existing home-built designs, if the alignment wasn’t exact, then the motion would bind, causing loss of steps in the motors. Since many of the parts I would be cutting would be extremely complex, lost steps would be a serious problem.

Contained: A jumbled mess of unorganized electronics boxes and wiring would not do.

Compact: I wanted to be able to bring the machine places for demonstrations. This meant that it had to be easy to transport and require no disassembly/reassembly.

Attractive: I’m a designer, so I just couldn’t bear the idea of something that looked cobbled together and poorly thought out. It might be homebuilt, but there is no reason it can’t look as good (or better!) as something commercially produced.

Can changes be made to the plans?

The following chapter covers design information, and part of the reason for including it is to provide some knowledge of why the design exists as it is, and why some aspects can and some cannot be changed. Many of the other plans on the market make a big deal out of stating that they can be modified to suit your needs. While this sounds great in principle, there are serious problems with this approach. The primary one is that changing the size of the machine can have serious negative consequences on its performance. In short, you should not make changes to these plans unless you really know what the consequences might be. The sizes of all components have been optimized for the overall size and use of the machine. Proceed to make changes with extreme caution and at your own risk.

If the seller of a set of CNC plans is telling you that it is acceptable to change dimensions at will, it is probably a good indicator that there has been no actual engineering done on the design. Worse yet, it probably indicates that the designer has no understanding of what even needs to be engineered and calculated, or how to go about it. The “design” is most likely the outcome of some trial and error, rather than being based on any kind of understanding of structural principles.

Assembly steps

The assembly steps in these plans start with the fabrication of the wood components and finish with the metal ones. I chose this sequence because it makes logical sense in showing a smooth, seamless order of building the machine. However, I would highly suggest reading through the entire set of plans and then deciding if this sequence makes the most sense for you. If you have any doubts about your ability to complete these plans then I suggest fabricating the metal components before the wood components. There are a couple of reasons for this: The first is that even though it may be more unfamiliar to many people, metal can actually be easier to work. It has no grain (as far as we can tell for our purposes) and is therefore predictable in its behavior. Most of the parts are aluminum, which is a soft metal and has relatively low cutting forces involved, much like those of a hard wood. The other reason is that fabricating the metal parts will constitute the bulk of fabrication time and require the most patience to maintain build tolerances. The number of cuts, holes to drill and tap, and amount of hand filing and finishing will ultimately end up being a considerable amount of tedious time consuming work. By the time you are finished with all of the metal components, the wood fabrication will most likely seem quick and easy.

This sequence will also quickly reveal whether you have both the skills and stamina to complete the metal components. It would be unfortunate to build the wood structure first, only to find out later that you really are not going to be able to complete all of the metal parts.

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Designing a machine:

For many designers of home-built machines, the design process goes something like this:

a. Look at a bunch of other designs that have already been built.
b. Cobble something together that looks similar.
c. Be disappointed.
d. (Hopefully) build a second one.

For the most part, even those with a lot of previous design experience follow part “a” and look at existing designs. But they do so with a higher level of knowledge and sophistication, and with a better set of existing precedents to follow, and therefore a much higher degree of success. Not many people actually break revolutionary new ground. However, that knowledge of engineering principles and design process is crucial even to the success of a design that falls entirely within a traditional, proven type.

Design Process and principles

Following is a brief attempt to explain my thought process and rationale for this design. So here is a list of points that just perhaps might help people design better machines or make modifications to these plans. They range from observations of typical problem areas, to design philosophy, to real formulas and engineering information. For those with engineering knowledge, please excuse my over-simplification of many things. This is aimed at those with little design expertise and isn’t intended to make anyone a capable engineer. Indeed, I myself am not an engineer and am in no way equipped to make someone else into one. Rather, it is intended to make it clear how complex it is to design something properly and how quickly you can get in over your head even when equipped with a little bit of over-simplified information. In short, keep your design hubris in check and aim for the cautious and proven path.

Woodworking skills

This may seem somewhat tangential to a design process, but it is not. I see many internet postings from people about wanting to build a CNC router to presumably use on wood, and they themselves have very rudimentary woodworking skills. Or those wanting to build a CNC milling machine who have never run a conventional mill through metal.

It is very important to know the behavior of the material you will ultimately be cutting with your CNC machine. A CNC router is a very advanced piece of woodworking equipment. Your success in using it is going to be much greater if you have an understanding of woodworking basics and a feel for the material. How can you hope to electronically control a 20,000 rpm blade through wood if you don’t have some basic feel for a hand tool moving through a piece of pine? Go out and buy a couple of good quality chisels, a hand plane, a good set of sharpening stones, a couple of good hand saws, a few layout tools, and try building something. Something with some precision joints. Make a nice little “simple” box with finger jointed corners. Go buy a copy of “A Reverence for Wood” by Eric Sloane. Make wood your new best friend. You are going to very quickly learn all about grain, how the tool wants to follow it, and why it is important to control machine backlash some way other than through electronic compensation. This is also going to improve your skills to build the actual machine.

Use the router to build the machine

If you are building a CNC router, then obviously somewhere along the line you are going to buy a router to use as the spindle. Buy it early and use it to fabricate the machine itself whenever possible. Many of the machine parts that are cut from plywood can just as easily be cut with a router as they can a circular saw or a table saw. In fact, you will probably get a much finer finished edge when cutting with the router. You’ll be amazed what you can do with a couple of clamps and a guide fence. More complexly shaped router guides can be made from masonite or even very thick chipboard. This picks up on the last point about getting to know how the tool works in the material. You will get to intimately know how a router works in wood. You’ll quickly learn if you need to move the tool left or right relative to the edge you are cutting (conventional cutting vs. climb cutting.) You’ll learn about spindle speeds and feed rates. You’ll learn about how to plunge into a workpiece. You’ll learn about different cutter profiles. You’ll get a sense of the forces involved in all of this, and they just might surprise you.

Stiffness

Speaking of forces, the biggest shortcoming I typically see in home-built machine designs is a lack of stiffness, or rigidity. Stiffness is the ability to resist deflection. Materials have "elastic" behavior. At its simplest, you push on them and they deflect. Let go and they spring back. Push too hard and it doesn't spring back (you have gone beyond the elastic limit and caused "plastic deformation" or went beyond its yield point. In other words, you've bent it or broken it). ALL machines have some amount of deflection. A machine built of HDPE plastic has tons of it. One of MDF still probably has lots and lots. Much more than should be acceptable in any material used for machine parts. A machine that is built of massive cast iron and costs hundreds of thousands of dollars still has some deflection, it is just infinitesimally small.

A lack of stiffness causes several problems. The obvious one is that if the machine deflects under a cutting load, then the tool isn't in the spot that the computer thinks it is. In other words, your cut is not going to be accurate. The other big problem is something called chatter. A machine is a dynamic structure, meaning there is motion involved. That motion can cause vibrations and oscillations if the machine can flex too much. If you have any amount of experience using hand power tools, you have probably encountered chatter, and have a tactile understanding of its problems. At best, it means that you have to slow down the cutting speed or take cuts that are not as heavy. At its worst it can destroy the part you are making or even cause damage to the machine.

Stiffness comes from a combination properties. The first is the flexibility of the material itself (called Modulus of Elasticity.) The second is how that material is arranged (called Moment of Inertia). Because stiffness comes from a combination of factors, it means that to some extent having a surplus of one property can make up for a deficiency in the other. What this means is that even a very flexible material can be arranged to produce a strong and rigid structure. This is why a machine built of MDF has to be so bulky and clunky looking. It needs to position the material in a way that can overcome its inherent weaknesses. Unfortunately this is still not as good as using an inherently stiff material in an efficient way. So yes, you can build a somewhat rigid machine out of wood. No, never as rigid as cast iron, nor as compact. We'll come back to stiffness in more detail later.

Joints

This is every bit as important as material choice. There is a huge difference in the amount of force that can be transmitted through different types of joints. Picture a butt joint vs. a lap joint vs. a joint with a gusset in it. One big limitation in using wood for any structural application, whether a machine, a building, or a piece of furniture, is designing adequate joint details. Subtle differences in how pieces come together can have a huge effect on strength. Head back out to the shop with those new hand tools you bought and throw together some different ways of connecting a couple of pieces of wood. Try bending, twisting, and otherwise breaking the joint and see which are strongest in which directions. Creating strong joints in MDF is no small undertaking, but it can be done.

Learn some structural design basics

Learn some basic principles of structures. Even simple stuff like this- Take a good old fashioned shoe box. Without the lid on it, hold at each end and twist. Notice how flexible it is. Now take the lid and tape it on. Tape all the way around at the seam. Now try and twist. Or take a simple ruler. Support each end on some books or something, so the ruler is lying flat. Push down in the middle and notice how flexible it is. Ok, now turn it 90 degrees so you are pushing on the thin edge instead on the face. No detectable deflection at all now, right? Take a piece of paper and hold it straight out from you. It just flops down, right? Put a 90 degree fold in it and try it again. Or just put a curve in it and try it. While these little demonstrations might seem overly simple, they give you some direct feedback and understanding that you don't get by just reading about things on the internet or in a book.

Build a model

No, I don't mean in SketchUp, Rhino, Solidworks, etc. I think one of the big problems that comes with the easy availability of 3d modeling software today is that it does not give any sense of materiality and how things behave in the real world. Everything works perfectly on the computer screen. The result being that people draw endless variations of a design without a real understanding of its shortcomings. There is never any improvement from one iteration to the next. If you are going to dedicate weeks or months of your life to custom designing and building a CNC machine, then take the time to build a small scale model of it before building the real thing. It is well worth the time. I'm really surprised that I never see this happen. Build it out of something flexible. I'd suggest something like 1/16" chipboard (this is the stuff cereal boxes are made from, you can get it at a good art supply store in many thicknesses), mat board, posterboard, or bristol board. Don't built it out of something stiff like foam core. You want to be able to see the exaggeration of where this design will flex. You don't need to build it so things slide or move. Pretend it is fixed in mid cut. Do try and replicate how the pieces of the material will really come together at the joints. Elmers works great to glue it together. After it has dried for a few hours, push on it from different directions and watch it flex. Ok, now that you have seen where it flexes, redesign it and build another model. Or add to what you have already built. I guarantee it will be a significant improvement. Or at least a much bigger improvement than if you had just done it all on the computer. (Yes, you can be using the computer throughout to draw the thing before you build the model.)

Break a model:

Getting a model that is feeling very rigid in your hands? Good. Now try and break it apart. Try and push in ways that would be somewhat similar to what cutting forces would do. If you really have to push hard, and it feels like it doesn't flex at all, and then catastrophically explodes, you are doing well. If it mushes and bends all over the place before finally breaking, you have some more design work to do. Now look at how it broke apart. Did it fail at the seams and joints, or did the material itself fail? If you have really done a good job, most of the joints will be intact and the material will have buckled, torn, sheared, etc. It is possible to build a posterboard model that is nearly impossible to break in your hands.

Matched level of components

I often see posts on web forums asking advice about things like using expensive high accuracy ball screws for motion control on an MDF machine. A machine should have a consistent level of inaccuracy in its components throughout. Many MDF designs have the potential for the machine frame itself to flex 1/8" or more under anything more than very light cutting loads. Under these conditions, any motion control system that is more accurate than simple threaded rod is total overkill. You will never see the benefit of the accuracy of those few components if the inaccuracy of the rest of the machine is off by orders of magnitude. The quality level of everything needs to improve together, otherwise you are just wasting money. Those nice ball bearing linear rails are pointless when bolted to a substrate that changes in size when it absorbs and loses atmospheric moisture. Here is a basic list of things that should have somewhat matched accuracy levels:

-Frame material.
-Rigidity of frame design (an independent thing from material!)
-Ability to align and adjust the machine.
-Type of guides (from drawer slides, to skate bearings, to precision linear rails).
-Method of causing motion (threaded rod, acme, cables, timing belt, ball screws).
-Backlash, or the amount of play in the machine.
-Electronic resolution of steppers or servos.
-Machine speed.
-Spindle power.

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Tolerance and accumulation of error.

Beyond creating a rigid machine that will not deflect under a load, there are other factors in design. One is the issue of tolerance. Many homebuilt machine designs claim something like this: “cuts accurate to .000025". This is complete nonsense. A number like this is merely a theoretical electronic resolution of the stepper motors. It just means you can move the motors controlling the machine in little tiny increments of that size. It in no way reflects how accurate, or inaccurate, the overall machine itself might be. It in no way translates to accuracy at the tip of the tool, which is where it counts. Sometimes inaccuracies will serendipitously cancel each other out. Sometimes something being inaccurate in one direction will be counteracted by something being inaccurate in the other direction, the net result being that the error is not large. But we can’t count on this happening, we have to plan for a worst case scenario. So what we need to do is to add up all of the possible causes of inaccuracy to arrive at a total possible inaccuracy number. Here are a few things that contribute:

-The machine flexing.- frame, motor mounts, etc.
-Play- space between bearings and rails.
-Linear motion inaccuracy. -rails not straight, variable diameter, not parallel or in-plane.
-Linear drive inaccuracy.
-Electronics error.

Degrees of constraint.

One common problem that I see in many DIY designs is machines that bind under a cutting load. The problem is this: The axes of the machine needs to smoothly roll on some sort of bearing system. And each axis needs to have bearings configured in a way that will constrain the motion so that it will only go exactly in the direction of that axis. However, this typically requires many bearings that are spread somewhat far apart. It is common for the force from the motors that is pulling the axis along its travel is not centered between the arrangement of bearings. Also not centered between the bearings is the resistance to movement, or the force of the cutting tool moving through a piece of material. This is called an eccentric load. And what happens is that under these loads, the machine can easily flex in ways that result in the bearings no longer being in perfect alignment with whatever they are rolling along. So the machine binds. The arrangement of bearings on my X axis are somewhat unconventional. What is happening is this: they are arranged so that the right side of the gantry is fully constrained. The gantry in effect is then cantilevered out from this set of bearings. The bearings on the left side of the gantry are basically outriggers that stabilize its position. The bearing configuration on the left is not fully constrained. This is intentional. It has been done this way so that the machine cannot bind if there is excessive flexing anywhere or if the cutting forces become too high. What this means is that while under these conditions there may be some inaccuracy in the cut due to deflection of the gantry, the machine will keep moving. I felt that it was a better compromise to accept this very minor inaccuracy rather than have the machine bind which most likely would result in a completely unusable part. When a machine with stepper motors binds, what can often happen is that the computer keeps feeding the signal to the motors because it has no idea there is a problem. If the machine suddenly starts to move again, it is now receiving code that is out of sync with where in the cutting process it left off. The result is a huge cutting error. I decided I would rather have the machine keep plowing through the cut even if the cutting loads were very high and there was some deflection, rather than have that very large discrepancy from binding.

Alignment.

Going hand in hand with machine binding is the problem of how to align a home built machine. Smooth bind-free operation requires accurate alignment between bearing surfaces on each axis. It requires getting the machine parallel, square, and in-plane. This can be a very difficult thing to accomplish. Nearly all homebuilt machines provide some means of providing adjustability. However, many use methods that make fine adjustment very difficult or impossible. Some do not provide enough directions of adjustability. The biggest problem is that nearly none of them provide any sort of reference plane to measure from. It does no good if the machine can theoretically be aligned, but there is no practical way of making measurements to find that alignment. I’ve attempted to solve these problems in several ways. I have used the factory faces of stock metal pieces to provide some amount of automatic alignment between parts. In other places slots have been provided to allow adjustability, or bolt holes are sized large enough to provide some play. All of the bearings have a set screw to allow very fine adjustments of their preload against the axis rails that they ride along. Finally, by pouring a thin layer of a very low viscosity epoxy on the bed of the machine, it can be used as a reference plane to measure from. All alignments are based from this one consistent plane.

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Structural design

Back to stiffness:
Rigidity:
To me this became the primary design factor. Everything springs from the stiffness of the machine. Accuracy goes hand in hand with flexibility. It does not matter if your electronics can control motion to .0001" if your machine frame flexes 1/8" under a cutting load. This seemed to be the biggest downfall of the existing homebuilt designs that I was seeing. Many machines were being built primarily of MDF (medium density fiberboard). This material is by nature very flexible. The manner in which it was being arranged was not doing anything to help the situation.

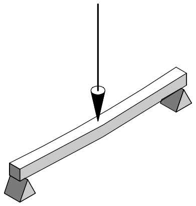
There are two factors at play here. One is a property called modulus of elasticity. This a property of the material and is essentially a measure of its flexibility. A higher number indicates a stiffer material. Obviously a stiffer material is desirable when we are building a machine. The second factor at play is something called moment of inertia. This is a measure of how stiff a *shape* or arrangement of the material is. The same amount of a material can be used with differing amounts of efficiency. Picture a simple wooden ruler. If you place it between two stacks of books, with the flat side of the ruler facing them, and press down in the center of the span, you will see it flex noticeably. If you stand it on edge and again try and press, it will not flex at all (at least not that you can see). The moment of inertia of the ruler is greater in one direction than the other. Another example would be to imagine a steel rod. If you were to try and flex a steel rod that is about 1/4" in diameter, you could easily flex and bend it. Now if we were to take that same amount of material and make it into a tube that is an inch in diameter, with a thin wall thickness, we can’t flex it by hand at all. Both have the same amount of material, but the tube has a much higher moment of inertia.

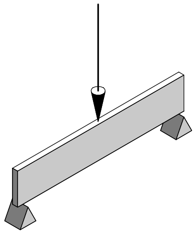
To get an idea of the range of material stiffness, here is a modulus of elasticity chart:

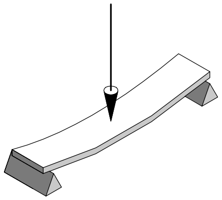
Rubber	1,500_15,000
Low density polyethylene	30,000
HDPE	200,000
Polypropylene	217,000_290,000
Nylon	290,000_580,000
MDF (wood composite)	530,000
Oak wood (along grain)	1,600,000
Pine wood (along grain)	1,300,000
Magnesium metal (Mg)	6,500,000
Aluminium alloy	10,000,000
Brass and bronze	17,000,000
Titanium (Ti)	15,000,000_17,500,000
Copper (Cu)	16,000,000_19,000,000
Wrought iron and steel	30,000,000

Looking at this chart the inherent problems of using materials like plastic or MDF when building a machine become immediately apparent. They flex like a wet noodle compared to even the most flexible of metals. My philosophy was to use materials of high modulus wherever possible. One counterintuitive outcome of this is that it is often actually cheaper to use small quantities of higher strength materials than large quantities of low strength materials. Designing using higher strength materials also allows the machine to be more compact, which can further help in reducing flex.

Please understand that the ability for a material to resist deflection is not exactly the same as its “strength.” These are two separate measures of material properties. For our purposes, the ability to resist deflection is what is more important. If there is enough material to provide a stiff enough design, there is very little chance of it not being “strong” enough, so we can ignore that structural need.







Moment of Inertia.
As briefly discussed on the previous page, the other factor in achieving stiffness is how the material is distributed. This is called moment of inertia. As I also mentioned, since most designs are driven by stiffness requirements rather than strength needs (the concept here is that if you built it so that it is stiff enough, it is going to automatically be strong enough) I'm focusing on that. Unfortunately, to compare the section modulus of even very basic design options against each other requires some math. So I'll briefly introduce a few simple equations. Since we are not dealing with "strength" there will be no bending moments, shear, etc. Hopefully this will give some (relatively) easy information to see the implications of design decisions. What happens if I make those rods twice the diameter? Is the same amount of material stiffer as a small solid bar or a bigger box section? How much more does it deflect if the span is twice as long? Here are the answers.

To find solutions to these questions we need two types of information. First is the modulus of elasticity, which is a property of the material. The second is the moment of inertia which is a property of the cross sectional shape of the part. This information works in combination with other factors such as the overall length of the part, how a load is applied, and how its ends are supported.

For example, lets take a simple piece of metal bar stock that has each end resting on a support. A load is pressing down in the center of it. So what factors make it flexible or stiff?

-Section dimensions. Increasing its size will make it stiffer. A 1" x 1" bar will be stiffer than a ½" x ½" bar.

-Section shape. Making the bar taller will make a much bigger difference in making it stiff than will making it wider. (Think back to the ruler example). Another good example of this is a floor joist. A 2x12 floor joist is going to be stiffer than a 2x6 floor joist.

-length. A longer piece is going to be more flexible than a short one.

-constraint. Our example bar is just resting on a support at each end. This means it can rotate slightly as the bar deflects. If the bar were held rigidly at each end, like if it was welded solidly to something, it would make it more resistant to flexing.

-load. A load that is spread out over the length of a member will cause less flexing than if it is all concentrated at the mid-point.

What we end up with is a three step process:

1. Look up the material's modulus of elasticity in a chart.

2. Calculate the section modulus based on cross section shape.

3. Calculate the deflection. The deflection formulas take many of the factors such as end constraints and loading conditions into account, so it is just a matter of finding the formula that matches the situation.

① Find modulus of elasticity

$$E =$$

LDPE	30,000
HDPE	200,000
Polypropylene	217,000-290,000
Nylon	290,000-580,000
MDF	530,000
Oak wood	1,600,000
Pine wood	1,300,000
Magnesium	6,500,000
Aluminium	10,000,000
Brass & bronze	17,000,000
Titanium	15,000,000-17,500,000
Copper	16,000,000-19,000,000
Wrought iron	30,000,000
Steel	30,000,000

Units:
All dimensions on this page are in inches.

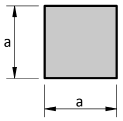
Modulus of Elasticity units are in lb/in^2

② Calculate moment of inertia

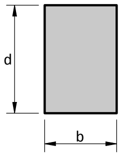
$$I =$$

cross sectional shape

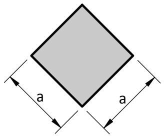
formula



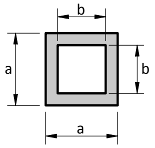
$$I = \frac{a^4}{12}$$



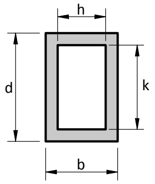
$$I = \frac{bd^3}{12}$$



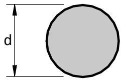
$$I = \frac{a^4}{12}$$



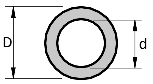
$$I = \frac{a^4 - b^4}{12}$$



$$I = \frac{bd^3 - hk^3}{12}$$



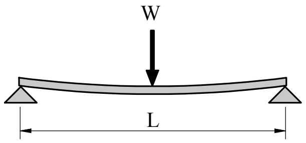
$$I = 0.049\,d^4$$



$$I = 0.049\,(D^4 - d^4)$$

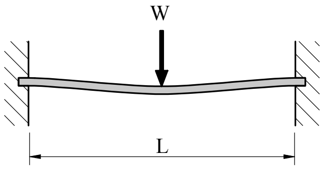
③ Calculate deflection

$$\text{max. deflection} =$$



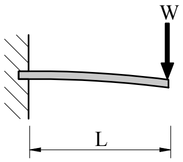
$$= \frac{W L^3}{48\, E\, I}$$

simply supported at both ends,
force applied at center of span.



$$= \frac{W L^3}{192\, E\, I}$$

fixed support at both ends,
force applied at center of span.

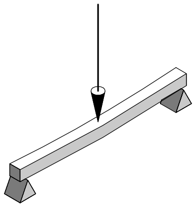


$$= \frac{W L^3}{3\, E\, I}$$

fixed support at one end,
force applied end of cantilever.

version 1.2

Example:



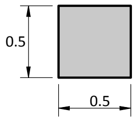
-simply supported at ends
-force applied at center

1/2" square aluminum

W= 10 lb at center
L= 24" long

step 1

Aluminum E=10,000,000

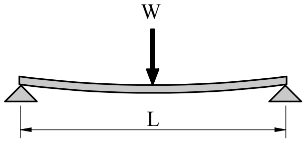


$$I = \frac{a^4}{12}$$

$$I = \frac{0.5^4}{12}$$

step 2

$$I = 0.00520833$$



$$= \frac{W L^3}{48\,E\,I}$$

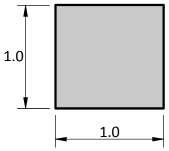
$$= \frac{(10)\ 24^3}{(48)\ (10{,}000{,}000)\ (0.00520833)}$$

$$= \frac{138{,}240}{2{,}499{,}998}$$

step 3

deflection $\boxed{= 0.055''}$

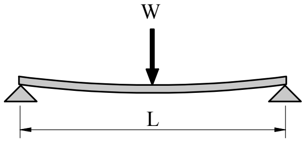
Now, lets change the material
to 1" square aluminum.
All else stays the same.



$$I = \frac{a^4}{12}$$

$$I = \frac{1.0^4}{12}$$

$$I = 0.0833$$



$$= \frac{W L^3}{48\,E\,I}$$

$$= \frac{(10)\ 24^3}{(48)\ (10{,}000{,}000)\ (0.0833)}$$

$$= \frac{138{,}240}{39{,}994{,}000}$$

deflection $\boxed{= 0.003''}$

Note that the original example had over 17 times as much deflection as the second!

version 1.2

structural design conclusion

Ok, so now that you are equipped with some basic formulas, it is time for the bad news. These calculations are great for very basic cross sectional shapes and simple loading situations. Essentially they are for finding deflection in simple types of beams. Unfortunately the real world is rarely that cooperative. As soon as the cross section becomes more complex (like an I-beam for example), or multiple pieces are attached together (like the gantry on this design) things become much more complicated. Determining the deflection in these composite assemblies is more difficult and is beyond the scope of this simple demonstration. Similarly, any introduction of loads other than the very idealized conditions shown in the formula diagrams also makes things tremendously more complicated and is beyond our scope.

More bad news. Not only do other situations complicate the matter, but there are complexities even within what seems capable by following these guidelines. For example, we have seen that increasing the size of structural element perpendicularly to its load is more effective than its width. However, there are limits to this. We cannot reduce the width too much or we run into problems. Picture an element that is many inches tall, yet only a few thousandths of an inch wide. By the calculations it might seem that it is sufficient to carry a desired load. However, it is thin enough that it is vulnerable to buckling and would need to be braced from the sides somehow.

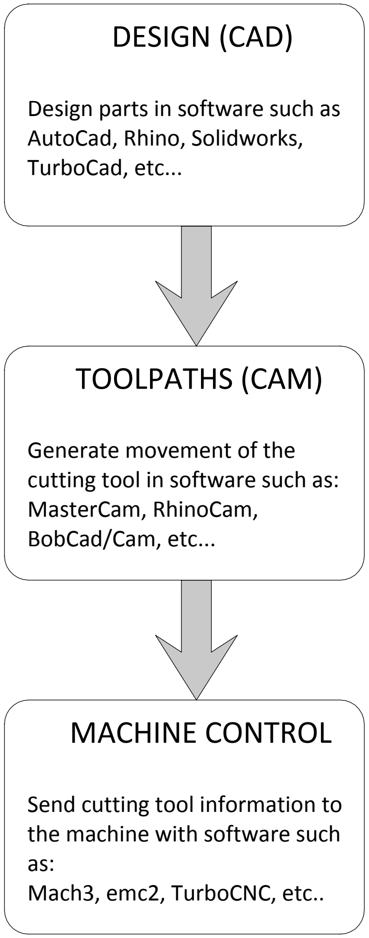
Even more bad news. It is unusual, indeed difficult, for any part to be designed so that there is only one type of stress involved. A good example of this would be a truss, which is designed the way it is so that its members are either in pure compression or pure tension. In practice this is very difficult to achieve and there is nearly always some amount of bending force introduced due to the realities of joint design. In our case, the gantry is a combination of torsion and deflection forces. Not only do the cutting forces push on it causing it to deflect, but those forces are not aligned directly with its centerline. The cutting forces are cantilevered some distance down the Z axis. This eccentric loading introduces torsional twist into the gantry as well. Understanding and calculating combinations of forces can be very complex and is well beyond the average homebuilders ability. It is important to keep in mind that this is nearly always the rule rather than the exception, so the structural calculations shown here should be viewed as a guideline for understanding some very basic principles, and for beginning to compare the effects of changing sizes of members. This should in no way be seen as a definitive guide for structural design, if anything it should be taken as an illustration of just how difficult it can be to understand even simple loads on a part.

A successful design also depends on creating joints that can transmit loads between parts in an effective and appropriate way. This is one other aspect that these simple calculations do not consider. Also keep in mind that all of this information pertains to static conditions. Remember that a machine tool is a dynamic condition and makes it much more complex to predict its structural behavior. Kinetic movements and rotating parts can introduce vibrations and oscillations that can amplify static stresses to the point of breaking things. Discussion of dynamic behavior is way beyond the scope of this set of plans.

As stated before, the intent of providing this information is twofold. First it is there to illustrate that what may seem simple can be incredibly complex to calculate and predict. Please keep that in mind when tempted to make changes. The second reason for providing this knowledge is that it gives a way of getting at least some sense of the implications of making changes. It is quite easy to do a few calculations and see that doubling the length of part makes it much more flexible. To directly see those numbers and be able to compare them may just aid in your judgement of how far dimensions can deviate from those in the plans, before the cross sectional size of member needs to change. In the ideal situation, this knowledge might help you improve upon the design as given.

version 1.2

SOFTWARE WORKFLOW


DESIGN (CAD)

Design parts in software such as AutoCad, Rhino, Solidworks, TurboCad, etc...

TOOLPATHS (CAM)

Generate movement of the cutting tool in software such as: MasterCam, RhinoCam, BobCad/Cam, etc...

MACHINE CONTROL

Send cutting tool information to the machine with software such as:
Mach3, emc2, TurboCNC, etc..

CAD = Computer Aided Design
CAM = Computer Aided Manufacturing

CAD/CAM Workflow

Designing your parts to mill

The parts you will ultimately be cutting with your machine need to start life somewhere, and that typically happens within some sort of design software such as Autocad, Rhino 3d, Solidworks, TurboCad, or even software such as Corel draw. The type of software you need will be driven in large part by the type and complexity of pieces you wish to be able to make. Very simple parts that are being cut from sheet stock can be designed in very rudimentary software that merely allows you to accurately draw two-dimensional lines and export that information in an appropriate file format. In fact, this is often referred to as 2 ½ axis milling, as most of the action happens in only 2 axis of machine movement. The spindle only moves up and down in the Z axis to enter the work at the beginning of the cut and to lift itself clear of the material at the end. Simple parts can be designed in Corel Draw, or one of the many freeware 2d drafting software packages available (take a look at DoubleCAD if you need a free 2d CAD package). Keep in mind that you generally get what you pay for with these tools, and any work beyond the most rudimentary parts will quickly run up against their limitations. They also may have problems in exporting the design information correctly in a file format that can be used downstream in your workflow (in the CAM software).

Creating the geometry for complex three dimensional surfaces requires a much more sophisticated software than is necessary for simple 2d linework. Software such as Rhinoceros 3d (Rhino) or Solidworks are powerful 3d modeling tools designed specifically to manipulate sophisticated topological geometries. Milling these surfaces is considered full 3d cutting, as the Z axis of the spindle is moving in careful coordination with the X and Y axis to result in the desired shape. These surfaces are often exported in other file formats such as .iges to preserve their topological data.

Toolpaths

The next step in the CAD/CAM workflow is typically to generate toolpaths, or the movements of the machine that are necessary to cut your part. This can happen in software such as Mastercam, RhinoCam, Bob Cad/Cam, MadCam, or a range of shareware programs. The geometry of your part is imported into this software. The following are basic steps that are often part of the workflow within a CAM software package.

1. Machine definition.

The software needs to know the configuration of the machine itself. While a few of the basic ones are only set up for 3 axis milling, more sophisticated software can handle more machine axes, or alternate configurations of how those axis move.

2. Stock setup.

The software needs to know how large your piece of stock is so that it knows how much material might need to be removed from around it. This is less important in basic 2 ½ axis milling, where it often really does not matter how large the stock might be. It is much more crucial when doing full 3 axis milling, especially if the surface contour that is being cut requires cuts that are deep enough that the tool or tool holder might collide with the piece of stock. So again, this is a situation of needing to match the abilities of your software to the types of parts that you want to cut. Complicated parts may even need to have additional geometry drawn in the design software, to provide additional cutting surfaces to remove material for needed tool clearance.

There are a couple of typical ways to enter stock size information within CAM software. One is to enter coordinates for the corner points of your stock size. Better CAM software can automatically detect the boundary size of your part and generate a stock size around that. In this case, it is often desirable to draw the uncut block of material in the design software so that the CAM software creates a material size that is what you desire.

version 1.2

3. Tool size.
The software needs to know the diameter and shape of the cutting tool. Many CAM packages have a library of tools from which you can pick the size and shape of your cutting bit. In others you may need to enter this information manually.

4. Cutting speeds and feeds.
Depending on a bunch of factors (the type of material being cut, the type of cutting tool, the rpm speed of the spindle, how much of the tool is being engaged in the material, and the quality of finish desired), the feedrate must be set for how fast the tool is pushed through the material. On most homebuilt machines the spindle speed is set at the router itself, so that does not need to be set through the software. The feedrate must be fast enough that the tool can efficiently eject the cut material away from the cutting area.

There are two methods of determining feed rates. The best method is to do a calculation for something called "chip load", which takes all of those factors above into account. This will give a fairly accurate number for setting feedrate. The other method is an empirical process where experience can provide an equally good feedrate number, or can aid in fine tuning the number that is arrived at by a chip load calculation. Unfortunately, in practice most homebuilt machines require neither method. They typically have a maximum speed that is far below running any danger of going too fast. So they can often simply be run at the highest feedrate that the machine will allow. If anything, homebuilt machines often have the problem of running so slowly that they can cause a poor surface finish because they do not remove material quickly enough. When cutting wood this can cause burning of the material.

5. Toolpaths.
The next step is typically to generate the actual paths that the tool will follow. With simple 2 ½ axis cutting this is a very simple process without many factors. Primarily all that matters if the size of the tool. More complex cuts open up a wider array of cutting options. A simple illustration of this would be milling out a pocket in a surface.

Roughing vs. Finish
When removing large amounts of material quickly, a roughing cut is often used. This is a fairly aggressive cut designed to remove stock around the final geometry quickly and efficiently. It may have the tip of the tool engaged deep into the material, and may step over as far as the entire diameter of the tool between passes. The roughing cut will then be followed by a finish cut which removes a much smaller amount of material, both in depth of cut and distance of step-over between passes. In a more professional setting there may even be a change of cutting tools between the roughing and finish cuts.

Plunging
When cutting geometries where the tool can not simply enter the workpiece from the edge of the stock, such as when cutting a pocket, the tool needs to make some sort of plunge cut into the material. The simplest method is to move the tool straight down into the material. This may or may not be the most appropriate method. Many cutting tools are not designed to be plunged straight down into material in such a way. A tool that can accommodate this move is referred to as "end-cutting", and can cut on its tip as well as its side. When the tool cannot be plunged, the tip will need to be gradually lowered into the stock as it is simultaneously moved in a sideways direction. This is called "ramping" into the material. The best CAM programs provide great control over how the tool can be ramped down into the material, including straight ramping and helical moves. It may also be desirable to avoid straight plunge cuts due to material properties. The grain of some woods may tear under such a tool movement.

Direction of cut.
If you have any experience with a handheld router, you will be aware of the difference between moving from left to right and right to left. One direction will be much harder to control. With a handheld router you would typically move left to right to maintain the greatest control of the tool. This is called conventional milling. If moving in the other direction ("climb cutting") the router bit may grab into the material and be pulled in an undesirable direction. However, when controlling the router with a machine the situation is not so simple. Depending on the circumstances, climb cutting may provide a much finer surface finish.

6. Simulation.
Many CAM programs have a simulation feature which will allow you to watch a 3d computer simulation on the computer screen of the tool cutting the material. This can allow you watch whether the tool is moving in desired directions and sequences, and if there are any possible collisions between the machine and the stock. The best CAM programs will automatically detect these collisions and provide a warning.

7. Post-processing.
Once all of the above steps have been finalized, and the operator is happy with the toolpaths, the final step is something called "post-processing." This is where the software converts all of that toolpath information into a format that can be read by software that controls the movements of the machine itself. This is typically some variation of an industry standard language called "g-code", which is a simple text file. G-code is nothing but a line by line set of numerical instructions for the machine to follow. It gives tool movement information in absolute coordinates, and may also provide information such as feedrate and spindle speed, and on more advanced equipment, moves such as toolchanges.

While G-code is a standard language, unfortunately each machine controller uses its own variation. The machine control software typically used by the homebuilder runs on a stripped down version that is often pretty close to pure g-code. More specialized machinery, which has its own control electronics rather than using a PC for control, often has a correspondingly more specialized version of g-code.

Like the need to match design software to the type of parts that you want to create, it may take some necessary care to match CAM software to control software. Problems may be encountered with finding CAM software that can handle generating toolpaths for complex geometry, yet has proper post-processing ability for control software such as Mach 3 or emc2 which are typical of what is used by the home user. Software that will accommodate very complex geometry may only have posts available for more industrial machine controls. This might mean learning enough g-code to be able to manually alter post-processed code for use in PC based control software.

Machine Control software
Mach 3, emc2, TurboCNC
This software takes the code that was generated by the CAM software (g-code) and outputs it as electronic signals that actually control the motors on the machine. This typically happens by sending "pulse" and "direction" signals through a parallel port cable to the machine electronics.

I use Mach 3 on my machines, and I feel it is one of the best bargains I've come across in software, as it is a very robust program and is affordably priced. Many people use the free demonstration version of the software, but I would highly recommend purchasing the full version if funds allow. The demo is crippled to running 1000 lines of code. This might seem like a lot, and might be sufficient for milling simple parts with mostly straight cuts, but you'll quickly find it severely limiting in cutting anything more complex. Even small parts with very complex 3d shapes may easily require tens or hundreds of thousands of lines of code. Another much less known, but just as important, restraint of the demo version is that it limits the processing speed of how quickly it outputs signals to your machine's motors. This directly limits machine performace.

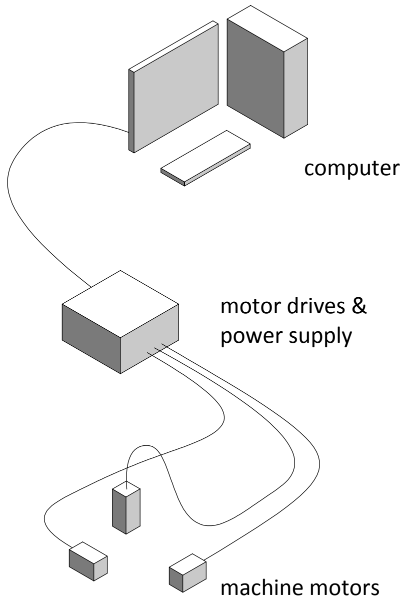
Software overlap.
Often software use isn't quite as cut and dry as the workflow diagram might indicate. Many CAM software programs provide tools for doing basic CAD work. While this can be handy for making minor changes after importing geometry to the CAM program, it is rarely powerful enough to use it as the sole design tool. Anything more than minor changes are best done back in the design software, and then re-exported to the CAM program.

Similarly, control software sometimes has basic tools for conversion of .dwg line drawings to g code. Again, this isn't the primary job of the software, so while it may work fine for very simple jobs, you should not rely on it exclusively. Control software typically also contains a g-code editor for more invasive manipulation of the code.

Cost of software.
As you might have surmised by this point, the cost of the software necessary to design, generate toolpaths, and then control the machine can be very, very expensive, especially if you want to cut parts of any complexity. I would highly recommend looking into both the costs of the softwares you might require and also downloading demo versions to try them out. Some are much more user friendly and intuitive than others which have very steep learning curves. There is little point in building a machine if you will not be able to use it for your intended purpose.

Learning g-code.
Another alternative when cutting simple parts is to hand write g-code. Doing this can eliminate the need for both design software and CAM software. Once upon a time, before sophisticated CAM software, this was how numeric machine control code was generated. The number of applications of this technique are probably limited these days, but it can be a useful method to know. Even if you never plan on hand writing numeric code, it can be useful to learn the basics of g-code. It can allow you to scroll through the code and spot problems, or to quickly modify parts of the code such as feed rates without having to go through the post-processing step again. If you have computer programming knowledge, learning g-code could also allow you to write your own scripts to generate toolpaths and g-code from within 3d modeling software such as Rhino.

Electronics



While an in depth discussion of machine control electronics is beyond the scope of these plans, an overview is important to get a basic understanding. For the most part, this discussion will stay somewhat abstract, although in the discussion of machine assembly I will briefly cover the installation of a Xyoltex drive board, which is a popular hobbyist board and a good match for this machine. As this is just intended as an overview, I highly recommend purchasing a kit from a supplier that includes all of the electronics as a matched collection.

While components of an electronic drive motion control system for a homebuilt CNC machine can vary widely, the abstract diagram to the left illustrates the basic principles of what is included.
These, in general, are:
1. A computer to send motion data to a “drive” hardware device.
2. A power supply to provide the required voltage & current to the motors.
3. Electronic motor drive(s) that sends the motion data to the motors at the required voltage/current.
4. The motors.

This is the general flow of information from the computer to the motors. In addition, there is typically some amount of hardware to provide data feedback from the machine to the computer. All systems should be equipped with limit switches to provide safety to both the machine and operator, while more sophisticated drive systems may have feedback sensors that give more accurate control of the motor positioning.

Working backwards from the motion of the machine:

Motors.
Most homebuilt machines are controlled by stepper motors. These are simple type of DC motors that require a pulse of electricity to move them one “step”. A typical stepper motor has 200 steps per revolution, so to cause continuing rotation in a stepper motor it requires a fast stream of electrical pulses. The frequency of the pulses will determine the motor speed.

These motors are easy to electronically control and relatively inexpensive, but they do have some drawbacks. One is that there is the possibility of them “losing steps” under a load. The stream of electrical step pulses is continuing to flow to the motor even though it temporarily being prevented from moving. Since the number of steps required to move the machine is very high, a very small number of missed steps may not have any noticeable impact on the finished part. On the other hand, enough missed steps may be catastrophic. In the best case, it may result in a less than perfect part, and at the worst it may result in machine collisions as its location is not corresponding to where the software thinks it should be. Missed steps is a problem with stepper motors because they typically lack any sort of feedback mechanism. They simply do as they are told, and there is no way of recognizing any error that may occur or way of correcting the motion. Some more advanced systems employ a sensor that informs the software of the position of the motor so that it can compensate for any deviation and get it back on track.

Another problem that steppers often suffer from is something called mid-band resonance. This occurs when the frequency of step pulses causes a dynamic resonance within the motor. This may cause it to move erratically or even lock up completely. This is obviously an even bigger problem than a few missed steps. Some stepper drives have circuitry that is designed to combat this phenomena. Most hobby level drives do not.

Most industrial machines use servomotors rather than steppers. They do not run in discrete steps like a stepper motor, but rather are more similar to a conventional motor design. These can be either DC or AC designs, and typically run at a much higher rpm than steppers, necessitating a gear reduction of some sort. Due to both of these factors, servo motors consequently have a much smoother operation than steppers. The major advantage of servos is that they typically have a positioning feedback loop. They have a device called an encoder that monitors the position of the motor. Any discrepancy between the theoretical position of where the motor should be and where it is measured as being can be compensated for, bringing it back to where it should be. However, servos are still much more expensive systems to set up on a homebuilt machine. They require more sophisticated electronics equipment to drive them and more knowledge to set them up and “tune” them.

version 1.2

Torque curve & power transmission

Like all electric motors, stepper motors have the characteristic of producing the greatest amount of torque at zero rpm. What this means is that the faster the motor turns, the less torque it produces. Manufacturers provide graphs that show their motors torque output relative to rpm. Not all motors are created equal, as some have torque output that falls off much more quickly as rpm increases than others. What all of this means is that when designing a power transmission system it is crucial to know what rpm the motor will be turning for a given feed rate of the machine. "Gearing down" the system may not necessarily increase the machine's "power" as the decrease in the motors available torque at a higher rpm may be greater than the mechanical advantage that is gained. However, even though the motor produces most torque when barely turning, the machine cannot be geared to have the motor at that speed. If the motor is turning that slowly then the distance between each "step" of its movement will translate to too large of a movement at the tool. It will not have a fine enough cutting resolution. So the system becomes a compromise between several factors.

The belt drive system on this machine was designed with exactly these factors in mind. It is what I feel to be a good compromise between speed, power to push a tool through the material it is cutting, and avoiding motor speeds that would be vulnerable to mid-band resonance. I also felt the belt drive was advantageous over a lead screw system in that it is more tolerant of misalignment. A lead screw must be aligned exactly parallel to the machine axis it is powering. By contrast, the belt can be out of alignment by a significant amount with zero negative impact on machine precision or performance. Although misalignment will have a significant impact on belt wear.

Drives

All motors that are used for motion control require some sort of electronic drive board to control them. Those for stepper motors typically operate on the principle of pulse width modulation (PWM.) Essentially this is analogous to turning a switch off and on at a very high rate of speed, resulting in an output stream that appears "smooth." These are often referred to as "chopper" boards, as they essentially chop the signal off and on very quickly. Drive boards take a variety of arrangements. They may incorporate control for several axis on a single board, or may be an individual board for each axis.

The advantage of individual boards per axis is that they can be replaced individually in case of damage. All drive boards do essentially the same thing. They receive input signals from the control software, which are low in voltage and current, and in turn output these signals to the motors with enough voltage and current to actually operate. As such, they mediate between the computer and the machine. Their in between position also allows them to handle signal inputs for additional functions such as emergency stop buttons and limit switches. Most drive boards are very vulnerable to any errors in mis-wiring. Incorrect connections, or breaking a connection to the motors while under power, can cause an immediate destruction of the electronics on the board. Follow manufacturer directions very, very carefully.

Microstepping

Another thing that many drives do is to break up the number of steps per revolution that are required at the motor into a greater number. So for instance, a drive may have 1/8 or 8x microstepping, which would effectively increase the number of steps per revolution that control the motor from its original 200 to 1600. This obviously is advantageous in that it increases the resolution of the system and provides finer control over the movement of the machine.

Power supply.

This is as simple as it sounds. A transformer type power supply device that is matched to the needs of the driver board(s) and motors. It is worth noting that most pulse width modulation boards actually perform most efficiently at the upper limits of voltage that they can handle. In other words, running them at lower voltage will not necessarily provide any additional protection for the board. Stepper motors also commonly require many times more voltage than their ratings may indicate. For instance, a stepper motor that is designated as a 2.5 volt motor may require more like a 24 volt power supply to efficiently power it.

Breakout board.

Simple drive boards such as those that have multiple axes self-contained on a single board may be able to directly connect to the computer's parallel port via a cable. Drivers for individual axis may require an additional piece of hardware called a breakout board. This is merely a device that connects to the computer via a cable and then provides multiple connections to wire the drives, stop switches, etc. These boards also often provide an added layer of protection between the higher voltage drive boards and the vulnerable low voltage computer. They do this through optically isolated connections.

Additional switches.

Drive boards or breakout boards will furnish some means of wiring in several important additional devices. An emergency stop button should be part of every system. It is typically a big red mushroom shaped button that will hopefully never be used, but provides an immediate way of shutting down the machine in case of an emergency. It should be placed in a location that is easily accessible while operating the machine. It can be wired to shut down all axis of machine movement, and can usually also be wired to shut down power to the router to kill the spindle movement. If at all possible, your e-stop button should be wired in this manner.

The other switches that should be wired into the system are limit switches. These are placed at the end of each axis's range of movement, thus a 3 axis machine will typically have 6 switches. These will stop the motion of the machine if it unexpectedly reaches the end of its motion. This can prevent serious damage to the machine as well as guarding against personal harm from broken cutters. In addition to acting as safety devices, these switches can do double duty as homing switches. These are used to return the machine automatically to its home XYZ position.

The computer.

All of these inputs and outputs either originate or terminate in the control software in the computer. Most control software for homebuilt machines is written to be used on PCs, although Mac versions are becoming available. The most popular, Mach 3, is designed for Windows based machines, and others such as emc2 are Linux based. You will typically need a computer with a parallel port for output to the machine electronics. The computer need not be the latest model, and in fact an older model with Windows XP or even Windows 98 may be preferable with some software. A desktop model is generally better than a laptop, as most laptops do not have a high enough voltage output through their parallel ports (if they even have one) to perform well.

Machine enclosure and sound transmission principles

One of the important considerations in this designing of this machine was the necessity for it to be covered. This was for the containment of both dust and noise. I have seen many home-built designs on the internet that have also attempted to provide a cover for these reasons. However, there seems to be a huge misunderstanding of the basic principles of sound control. This is evidenced by the technique that nearly all of these builders have adopted: they line the inside of the machine surround with foam-rubber acoustical "insulation." This is the stuff that has the familiar “egg-crate” surface texture. Unfortunately, this is an incorrect application of this material.

There are a couple of different types of “sound control.” First is the controlling of sound within a space. Sound waves bounce off of surfaces and it is often desirable to have a certain type of control over how this happens. The more times a sound bounces off of surfaces before it reaches your ear, the longer the “reverberation time” is considered to be. Sometimes a longer reverberation time is desirable, like in some types of concert halls, and at other times a short or zero reverberation time is needed, such as in a recording studio which must be free of echoes. Lining walls and ceilings with a material that absorbs sound waves will prevent them from being reflected back to a listener, and makes the space more acoustically “dead.”

The other type of sound control is between spaces. This is sound transmission. An example of this would be a situation like adjoining hotel rooms, where it is desirable to have as little sound make its way from one room to another. This is a completely different situation from controlling sound within a space, and this is what we are concerned with in our machine enclosure. We want to prevent the sound from being transmitted through it. The foam insulation that most builders seem fond of using is designed to control reverberation within a space. So this is great to use if you plan on being inside the enclosure with the machine. Otherwise, mostly it is just going to collect lots of dust.

So how do we control sound transmission? There are three primary categories:

1. Distance
2. Isolation
3. Mass

The first one is pretty obvious. The farther away we are from something the quieter it is going to sound. So if we put our machine a mile away we won’t hear it at all. This category clearly isn’t of much help to us.

The second one is very important when it comes to machinery. Vibrations can be transmitted through materials and cause new vibrations to be produced a distance away. These new vibrations produce sound. An example of this would be the bass on a neighbors stereo. This is also how the tin can telephone works. To combat this, many pieces of equipment have isolation mounts that damp vibrations. These may be made of elastomer materials such as rubber, use springs, or may use hydraulic devices. So even if we contain all of our sound within our enclosure, bolting it rigidly to a workbench could have the effect of turning the workbench top into a large sounding board.

The third category is the one that we are interested in. Increasing mass is a very effective way of preventing sound transmission. Hotel rooms that are separated by concrete walls are going to let less sound through than wood framed ones. So the ideal situation is to make our enclosure out of a thick, massive material. Unfortunately we have a problem with this. We want to be able to see into the enclosure. This necessitates using some quantity of clear polycarbonate material which has low mass. Thicker plastic would certainly help, but this gets very expensive very quickly.

So what interests us most is actually a sub-category of increasing mass, and that is the removal of any gaps or cracks. A gap is obviously a zone of zero mass and has a huge consequence on sound transmission. It has such an impact, that a 1/32" wide crack in a wall can allow more sound through than the entire rest of the wall. So what we need to do is to seal our enclosure as best we can. The tighter it is, the more effective it is going to be at preventing sound transmission.

So what is happening when people put that foam insulation on the inside of their machine enclosures and see an improvement? They are seeing small gains for a couple of unintentional reasons. Depending on how it is attached, it may be preventing surfaces of the enclosure from vibrating and producing sound. In effect it is providing some damping. More importantly it is helping with the mass issue. While it is providing a tiny bit of direct additional mass, more productively it is covering up gaps. Unfortunately, they probably could have achieved better results with something as simple as a roll of masking tape or silicone caulk.

GENERAL NOTES

- Do not measure off of printed drawings. Use dimensions as indiacted on drawings. Scale is not indicated on drawings due to variation in printer accuracy. Printing at 100% scale factor may not guarantee exactly 100% on paper!

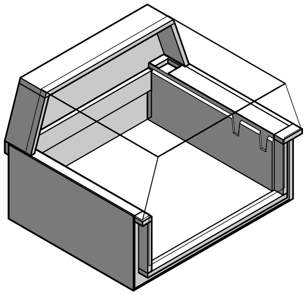
-Do not make changes to the design. While changes may make intuitive sense to you, resist the urge to do so. This design was carefully designed such that all components work together. Changing anything may have unforseen implications later in the build process, or may negatively affect the operation of the finished machine.

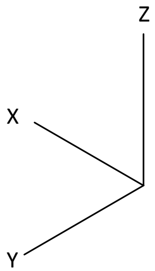
-Dimensions on mechanical parts are given in Imperial decimal units. Dimensions are given to either 2 decimal place accuracy or are given as full decimal eqivalents to fractions. This does not indicate degree of tolerance required.

-Tolerances. An acuuracy of +/- 1/32" is generally sufficient on metal parts. Any exceptions to this will be noted. This same level of precision should be aimed for in the cutting of wooden components as well.

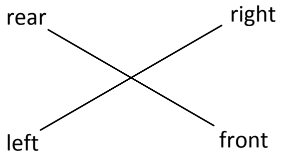
-Filing to fit. If tolerances are not held accurately enough it may be necessary to file some parts slightly during assembly.

-BE SAFE. Use good judgement while working and do not attempt anything that is beyond your ability that may jeopardize your safety.





Naming conventions for axis directions follow these standards throughout:



STEEL

1018 cold rolled rectangular bar

qty.	stock size
24"	.1875 x 1.25
24"	.25 x 1.50
36"	.25 x 2.50

A36 hot rolled angle

qty.	stock size
48"	1.25 x 1.25 x .125

ALUMINUM

6063-T52 rectangular tube

qty.	stock size
24"	1.50 x 3.00 x .125 wall

6061-T6 square bar

qty.	stock size
12"	.625 x .625
84"	.75 x .75

6061-T6 rectangle bar

qty.	stock size
6"	.125 x .75
24"	.1875 x 1.50
6"	.1875 x 2.50
24"	.1875 x 3.00
12"	.375 x 1.50
24"	.75 x 1.00
13"	.75 x 1.25
10"	.75 x 3.00

aluminum angle

qty.	stock size
88"	.75 x .75 x .0625

aluminum strip

48"	1" x 1/16"

PLYWOOD

birch finish quality

# shts	thick.	sheet size
1	1/4"	2' x 4'
1	3/8"	2' x 4'
3	3/4"	2' x 4'

HARDWARE

bolts

(14)	1/4-20 x 1/2"
(2)	1/4-20 x 1"
(30)	5/16-18 x 1 1/2"

socket head cap screws

(4)	#10-32 x 3/4"
(7)	1/4-20 x 1/2"
(1)	5/16-18 x 2 1/2"
(5)	5/16-18 x 3"

machine screws

(4)	#4-40 x 1"
(100)	#8-32 x 1/2"
(6)	#10-32 x 1"
(2)	#10-32 x 2"

set screws

(100)	#10-32 x 1/4"

nuts (nylon insert lock nut)

(4)	#4-40
(100)	#8-32
(8)	#10-32
(100)	1/4-20
(100)	5/16-18

flat washers

(100)	#8
(8)	#10
(100)	1/4
(100)	5/16

lock washers

(100)	#8
(20)	#10

lag bolts

(25)	1/4" x 1"

wood screws

(16)	#4 x 1/2"
(56)	#8 x 1 1/4"
(20)	#8 x 2 1/2"

nails

(box)	4d bright finish

MISC.

(2) 2' x 4' x 3/16" polycarbonate sheets
(1/8" thickness acceptable)
(shatterproof acrylic acceptable)

(46) sealed roller bearings
abec-7 skate 8mm x 22mm x 7mm

10 feet 3/8" wide x .200 XL pitch timing belt

12" 3/8-10 acme precision threaded rod

(2) 10 tooth timing pulleys, 3/8" wide, .200 XL pitch
bore dia. to match stepper motors

(1) derlin 3/8" acme anti-backlash nut
w/ .925" square flange

(1) derlin shaft coupler
stepper shaft dia. to 3/8-10 acme thread

108" 1/4" threaded rod

wood filler

carpenters wood glue

paint and primer

foam weatherstripping
3/8" x 3/16" roll

1 qt. low viscosity clear epoxy resin & hardener
<600 cps viscosity

24" piano hinge

(4) 1 1/2" utitlity hinges
(2) 2" utility hinges

(2) magnetic door latches

stepper motor wire

(6) limit switches

emergency stop switch

cable ties

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LIST OF FABRICATED PARTS

FABRICATED METAL PARTS

	part #	part name	# reqd.
GANTRY	01	gantry left bottom	1
	02	gantry	1
	03	gantry top left	1
	04	Y pulley spacer	1
	05	Y pulley flange	2
	06	Y motor mount rear	1
	07	Y motor mount front	1
	08	X belt clamp	1
	09	X belt plate	1
	10	gantry outer right	1
	11	gantry spacer	1
	12	gantry right top	1
	13	gantry right bottom	1
	14	Y rail	1
CARRIAGE	15	bearing block	3
	16	carriage block rear	2
	17	carriage block tapped	1
	18	Y belt clamp	1
	19	Z cable plate	1
	20	Z motor mount right	1
	21	Z motor mount left	1
	22	carriage block front right	1
	23	carriage block front left	1
	24	spacer	4
Z AXIS	25	Z rail	1
	26	Z rail block	1
	27	nut plate block	1
	28	nut plate	1
	29	router mount	2
	30	router clamp	2
X RAILS	31	X rail angle left	1
	32	X rail left	1
	33	X rail right	1
	34	X rail angle right	1
	35	X belt pulley flange	1
	36	X belt pulley spacer	1
	37	X motor plate	1
	38	X plate	1
	39	cable arm 1	1
	40	cable arm 2	1
	41	cable arm mounting block	1

FABRICATED WOODEN PARTS

	part #	part name	# reqd.
BASE ASSEMBLY	A	bottom skin	1
	B	Y rib 1	2
	C	Y rib 2	2
	D	X rib 1	2
	E	X rib 2	4
	F	top skin	1
	G	left bottom plate	1
	H	left rib 1	2
	I	left rib 2	2
	J	left rib 3	1
	K	left top plate	1
	L	right rib 1	1
	M	right top plate	1
	N	right rib 2	1
	P	right rib 3	1
	Q	right bottom plate	1
	R	left skin	1
	S	rear plate	1
	T	rear plate door	1
	U	left inner skin	1
	V	right inner skin	1
	W	right skin	1
	X	front plate	1
COVER	AA	front flange 1	1
	BB	front flange 2	1
	CC	front flange 3	1
	DD	front flange 4	1
	EE	front flange 5	1
	FF	rear flange 1	1
	GG	rear flange 2	1
	HH	rear flange plate	1
	II	rear flange 3	1

FABRICATED PLASTIC PARTS

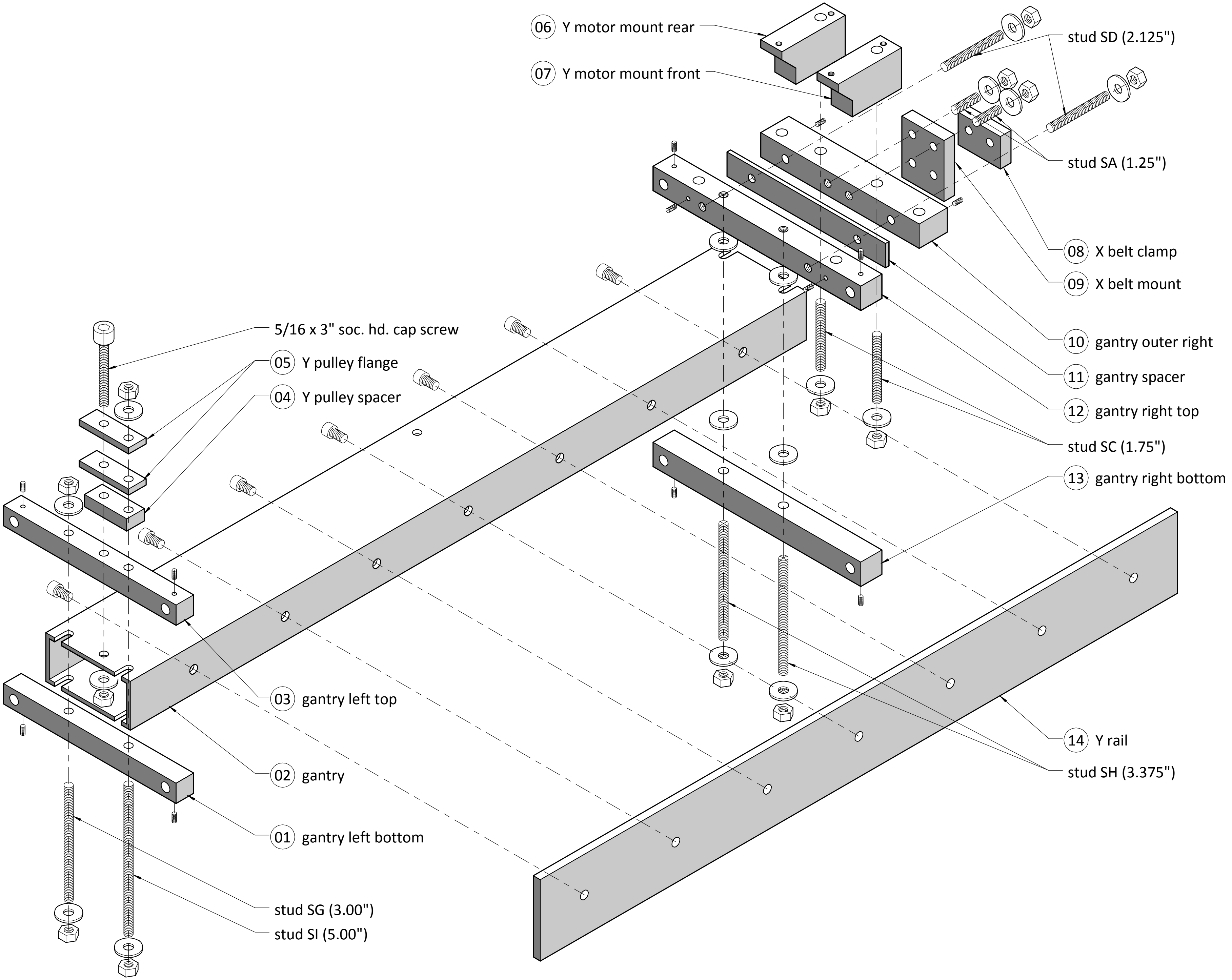
	part #	part name	# reqd.
COVER	P1	right skin door	1
	P2	cover left	1
	P3	cover top	1
	P4	cover right	1
	P5	cover front	1

MODIFIED HARDWARE

part #	part name	# reqd.
H1	thin head bolt	8
H2	shortened bolt	14
W1	enlarged washer	6

STUD SCHEDULE

	part #	length	# reqd.
1/4-20 studs	SA	1.25"	5
	SB	1.5"	6
	SC	1.75"	12
	SD	2.125"	2
	SE	2.5"	6
	SF	2.75"	2
	SG	3.00"	4
	SH	3.375"	3
	SI	5.00"	1
	SJ	8.00"	1



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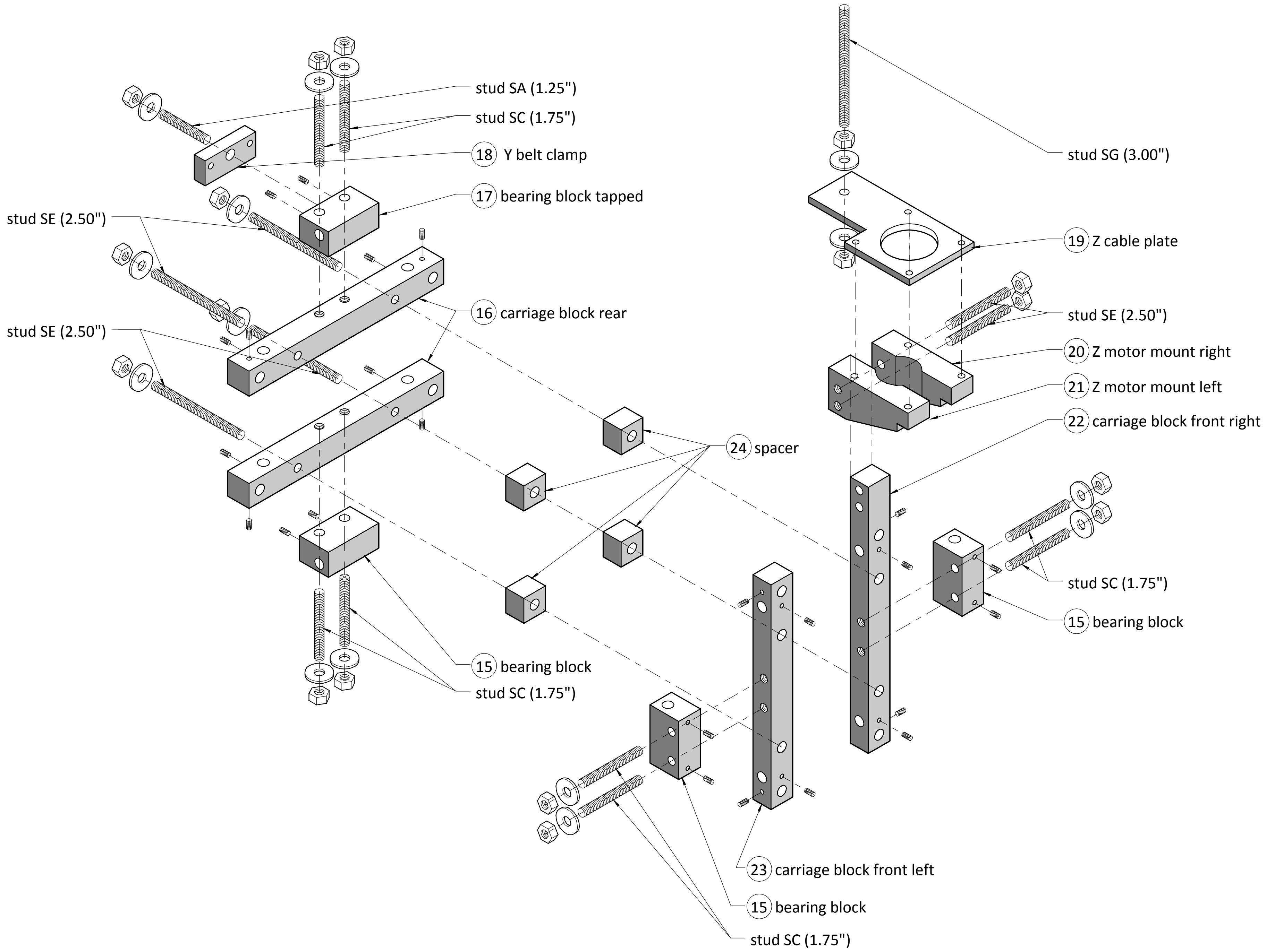
stud SA (1.25")
stud SC (1.75")
18 Y belt clamp
17 bearing block tapped
stud SE (2.50")
stud SE (2.50")
16 carriage block rear
24 spacer
15 bearing block
stud SC (1.75")
stud SG (3.00")
19 Z cable plate
stud SE (2.50")
20 Z motor mount right
21 Z motor mount left
22 carriage block front right
stud SC (1.75")
15 bearing block
23 carriage block front left
15 bearing block
stud SC (1.75")

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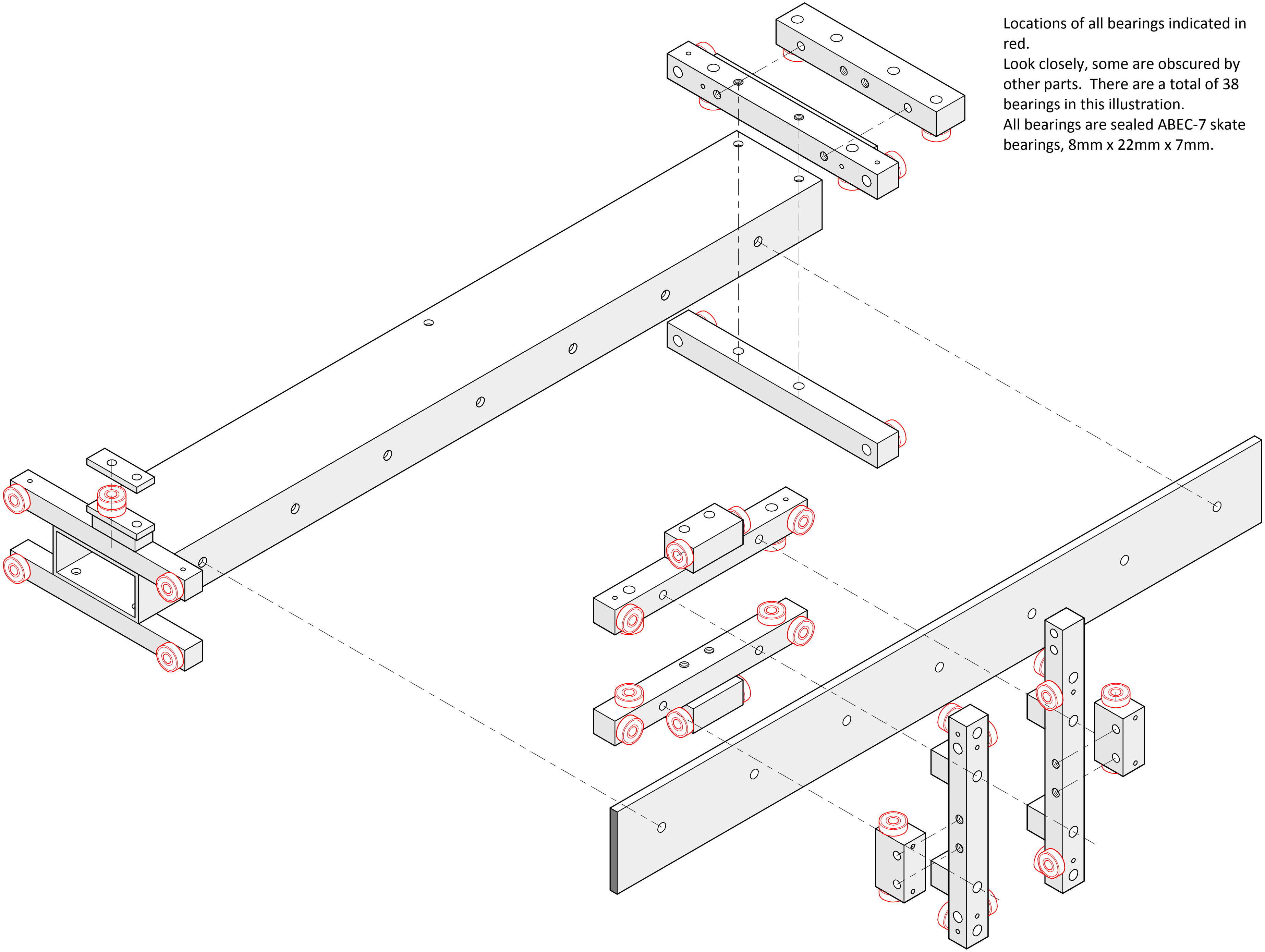
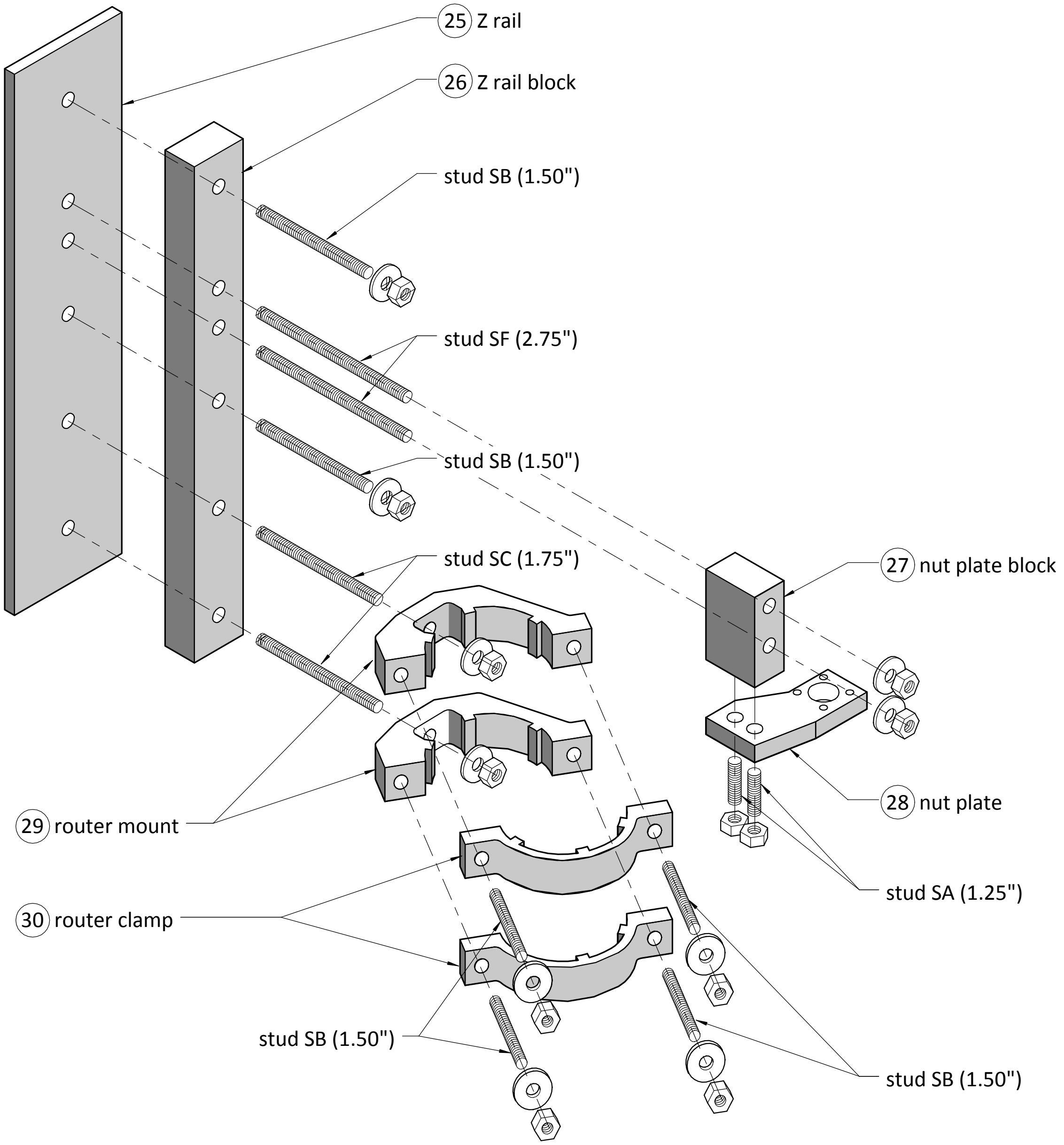


Locations of all bearings indicated in red.
Look closely, some are obscured by other parts. There are a total of 38 bearings in this illustration.
All bearings are sealed ABEC-7 skate bearings, 8mm x 22mm x 7mm.

version 1.2



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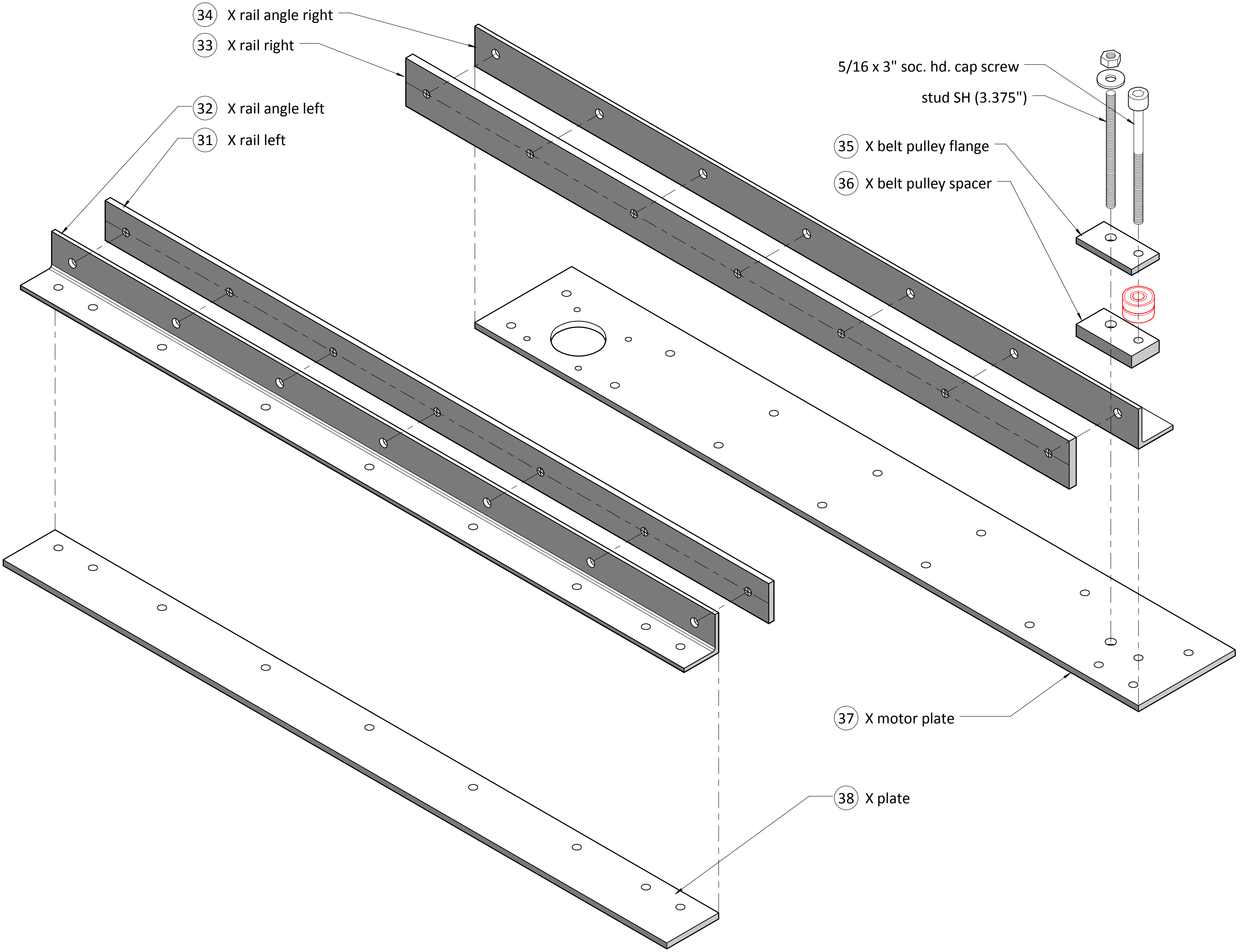

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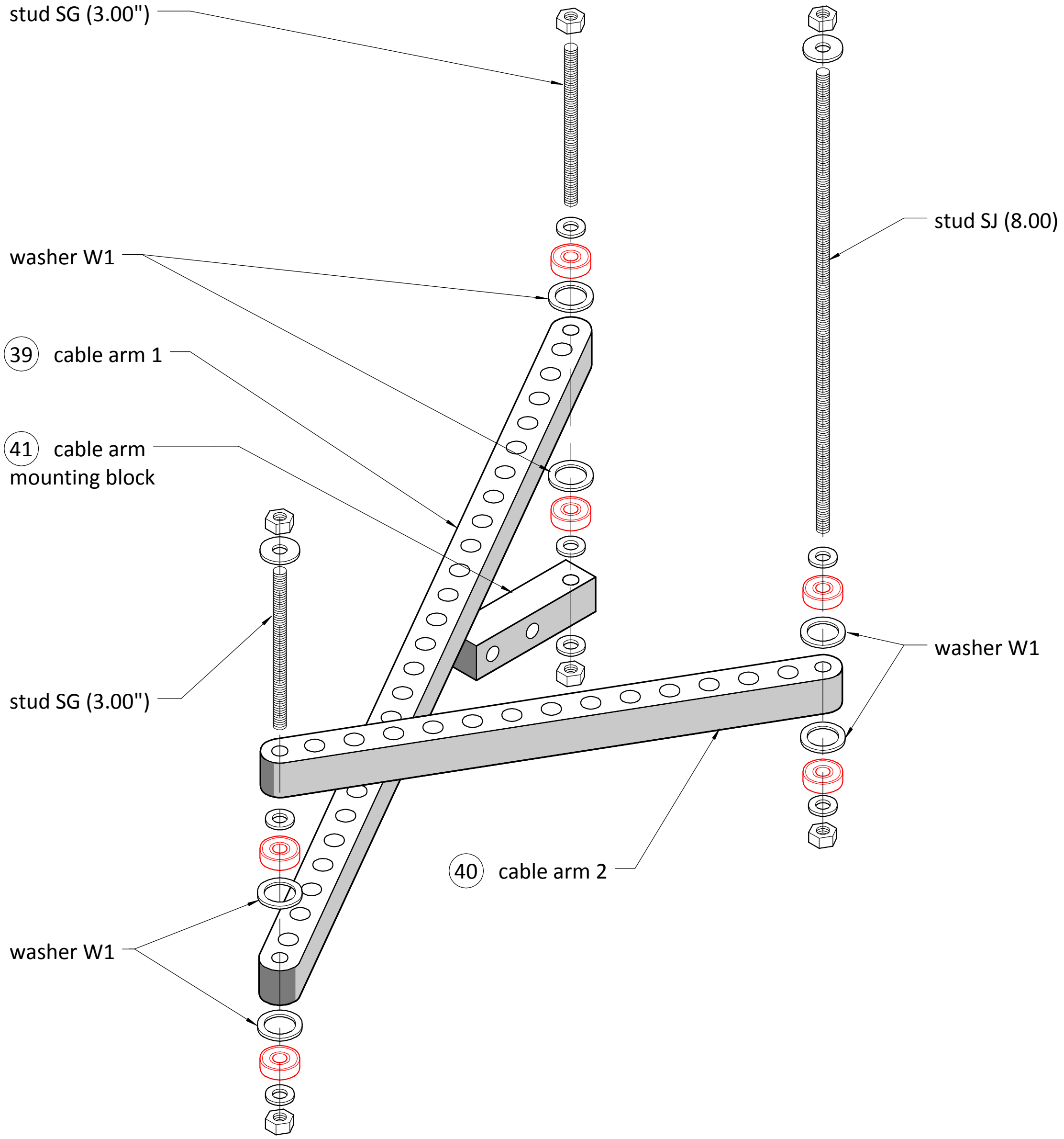
stud SG (3.00")
washer W1
39 cable arm 1
41 cable arm mounting block
stud SG (3.00")
washer W1
stud SJ (8.00)
washer W1
40 cable arm 2

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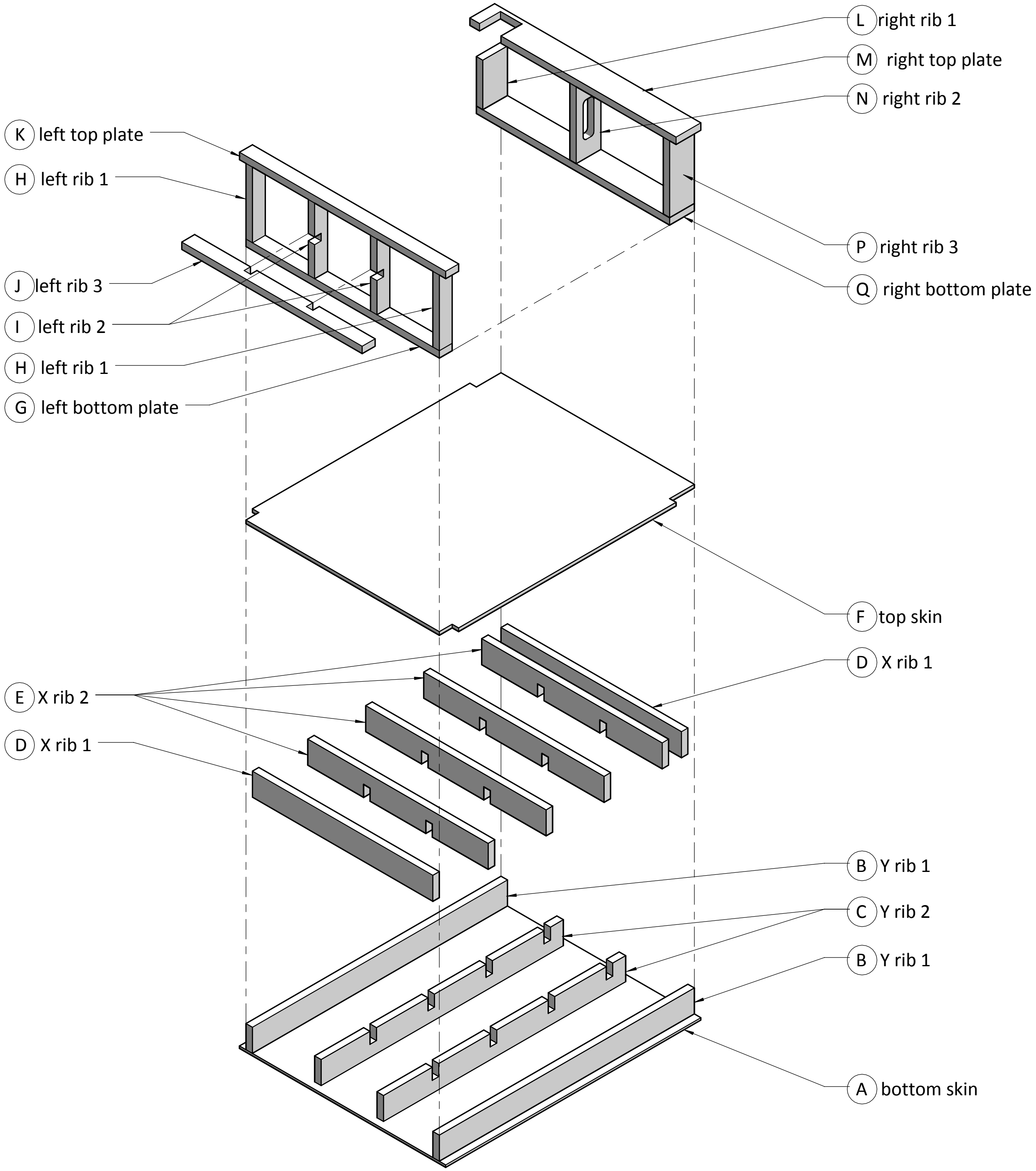

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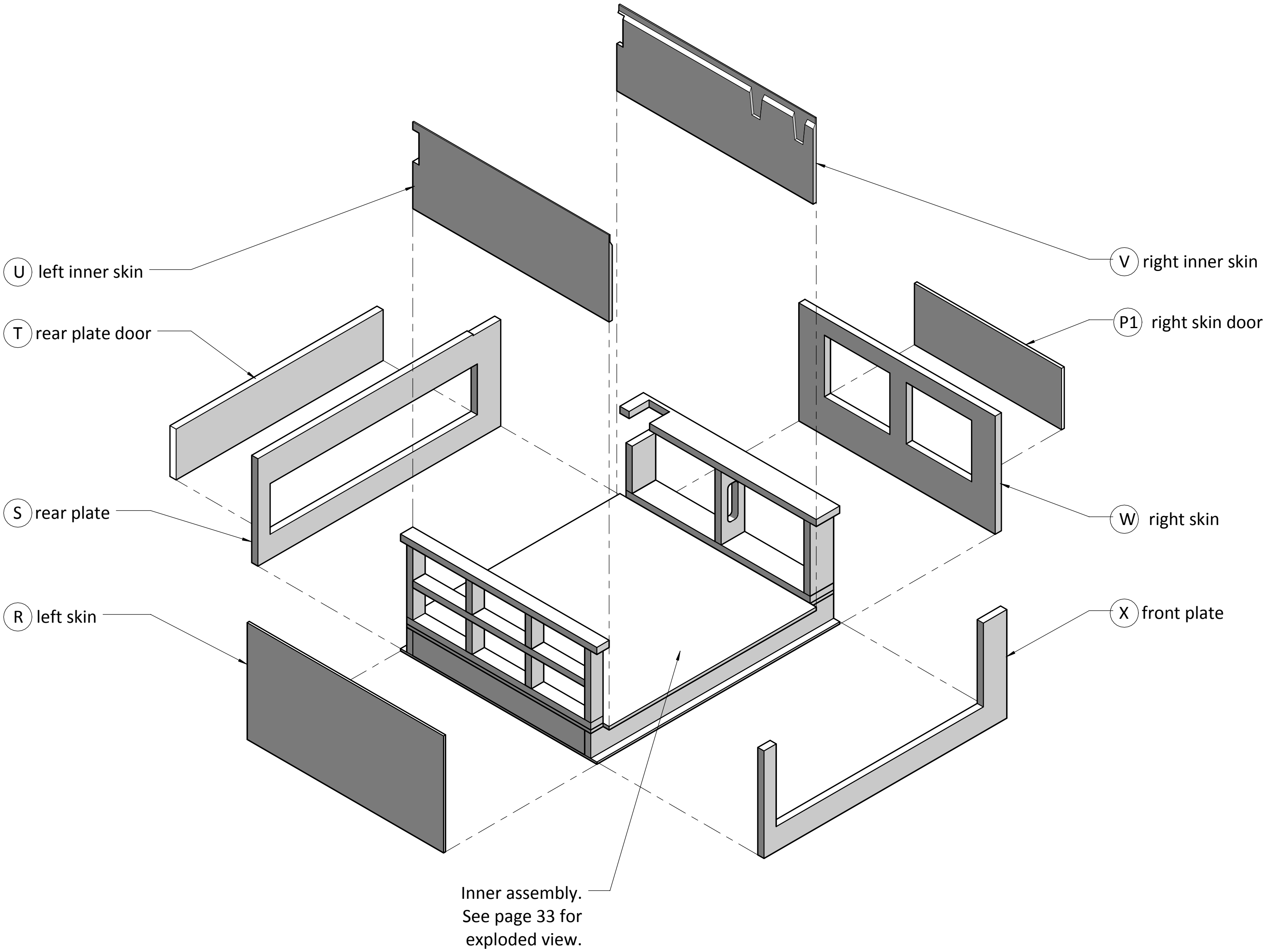
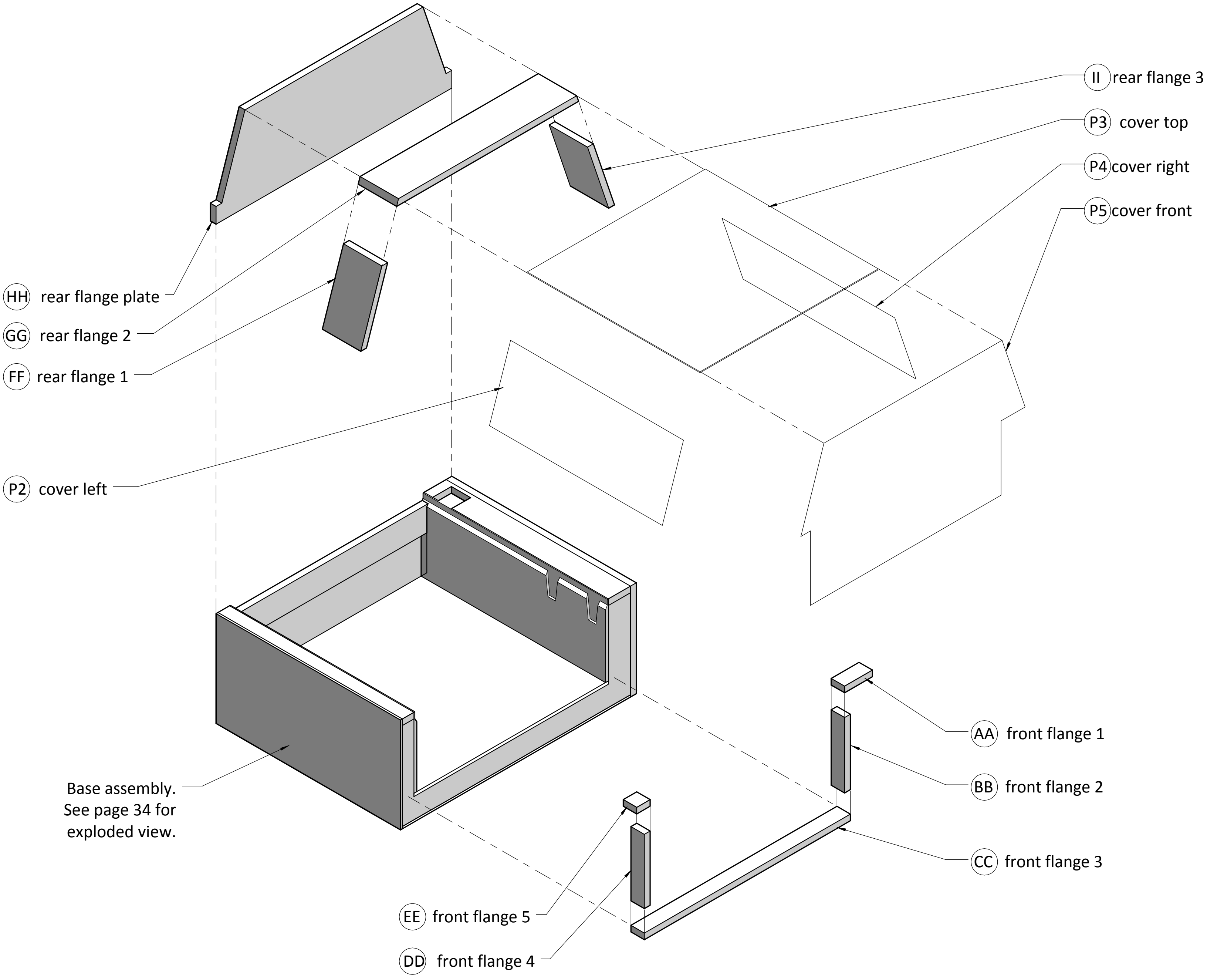
exploded base inner structure


U left inner skin
T rear plate door
S rear plate
R left skin
V right inner skin
P1 right skin door
W right skin
X front plate
Inner assembly.
See page 33 for
exploded view.

version 1.2



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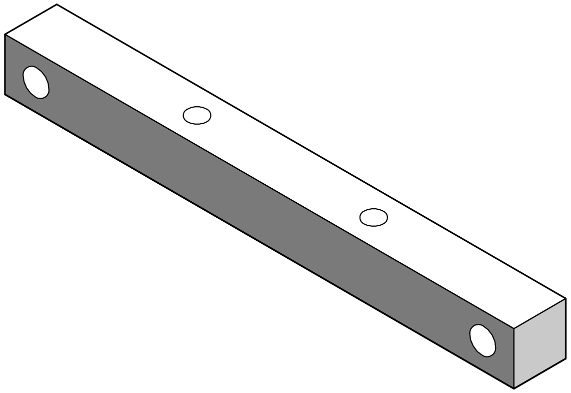

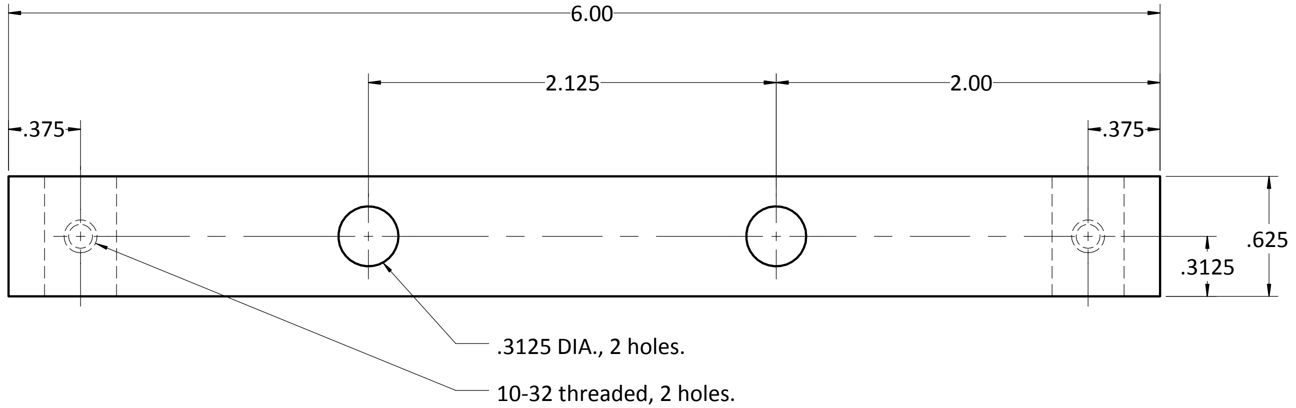

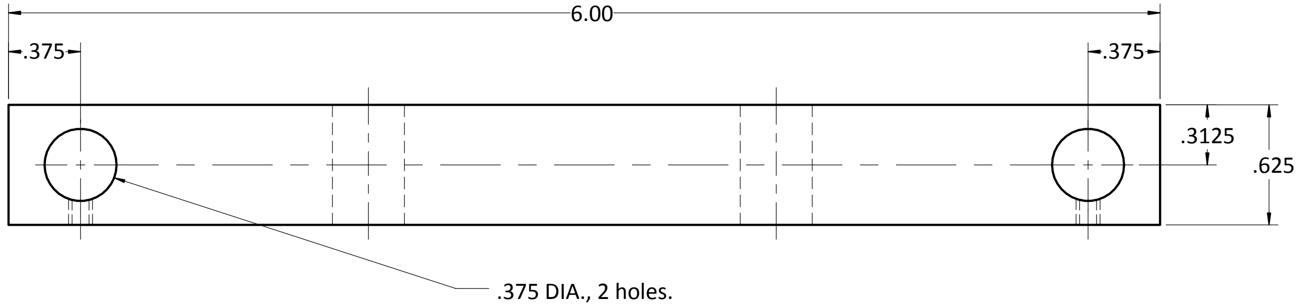

material:
6061-T6 alum.

stock size:
.625 x .625

# required: 1

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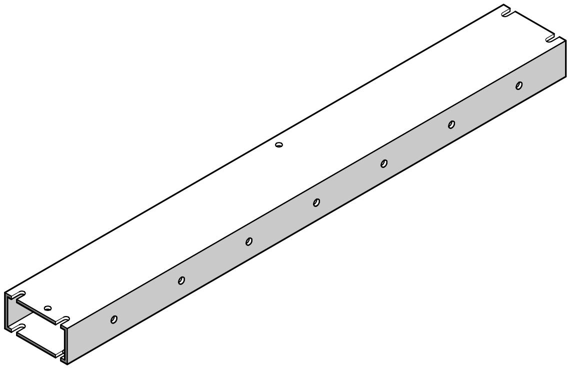
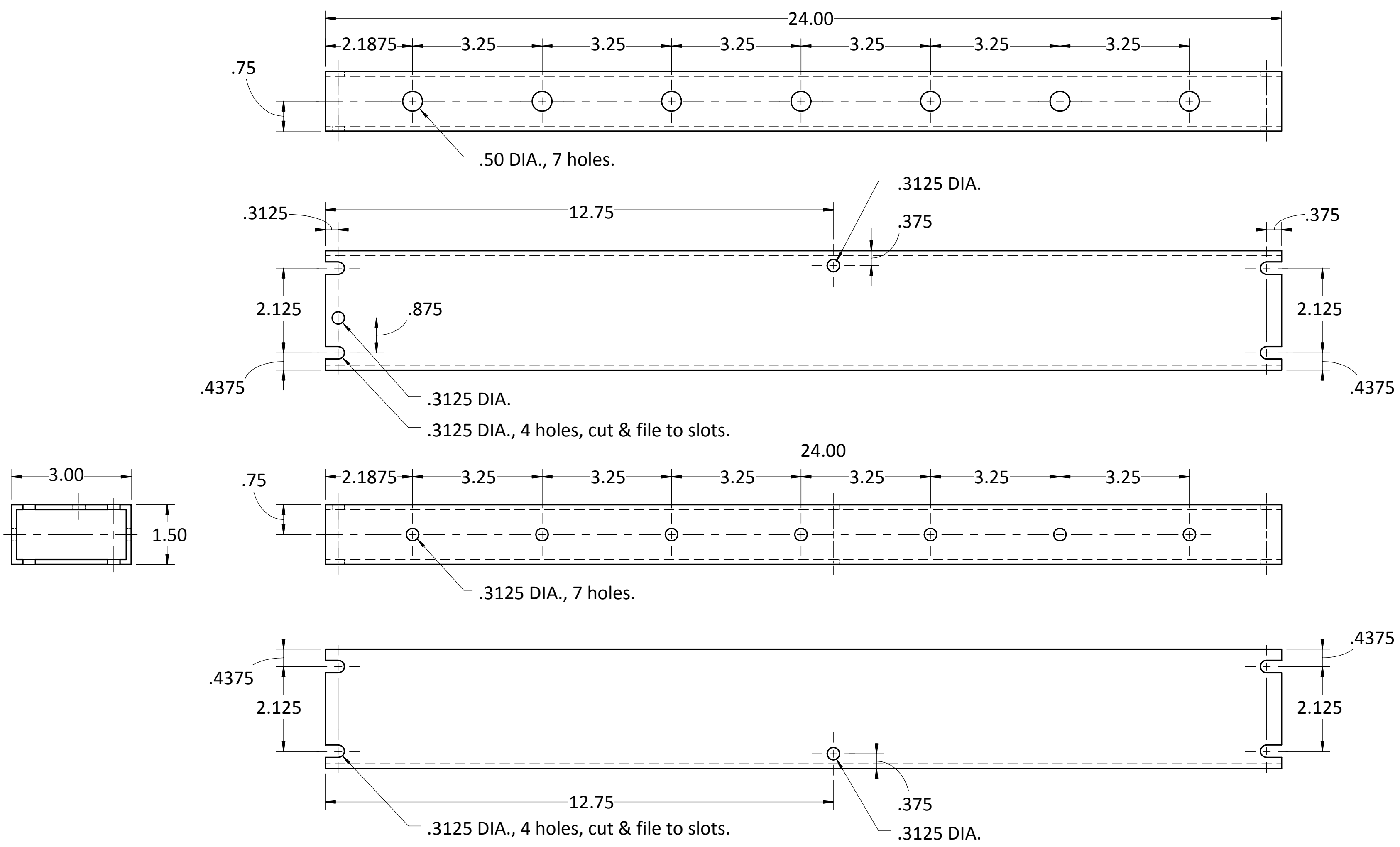
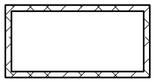
part # 1

1 gantry left bottom







material:
6063-T52 alum.

stock size:
1.5 x 3.0 x .125

# required: 1

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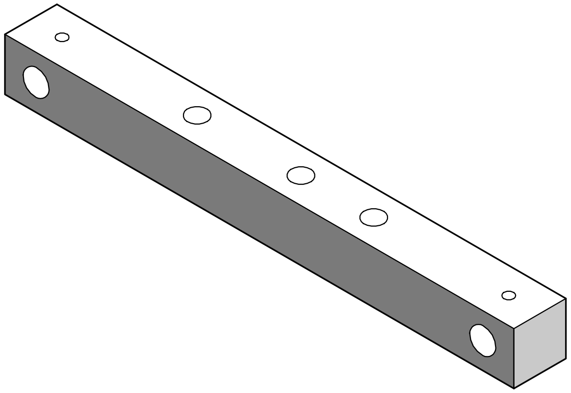
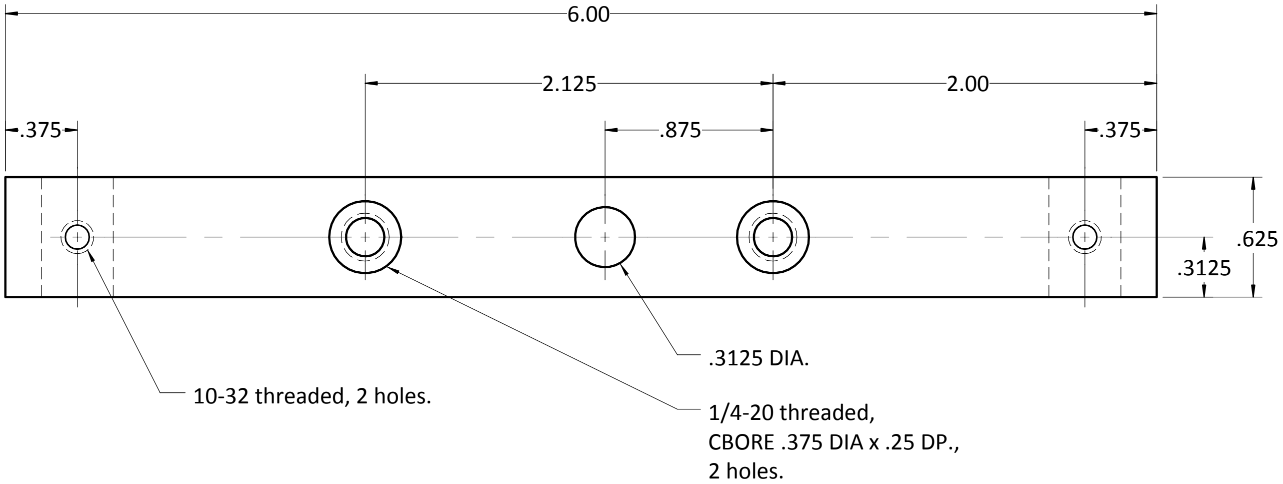
part # 2

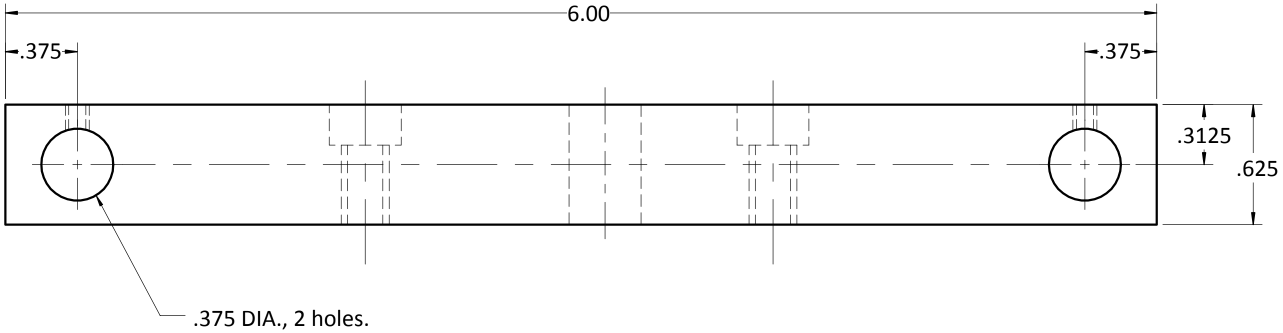




10-32 threaded, 2 holes.

.3125 DIA.

1/4-20 threaded,
CBORE .375 DIA x .25 DP.,
2 holes.



.375 DIA., 2 holes.

▨

material:
6061-T6 alum.

stock size:
.625 x .625

# required: 1

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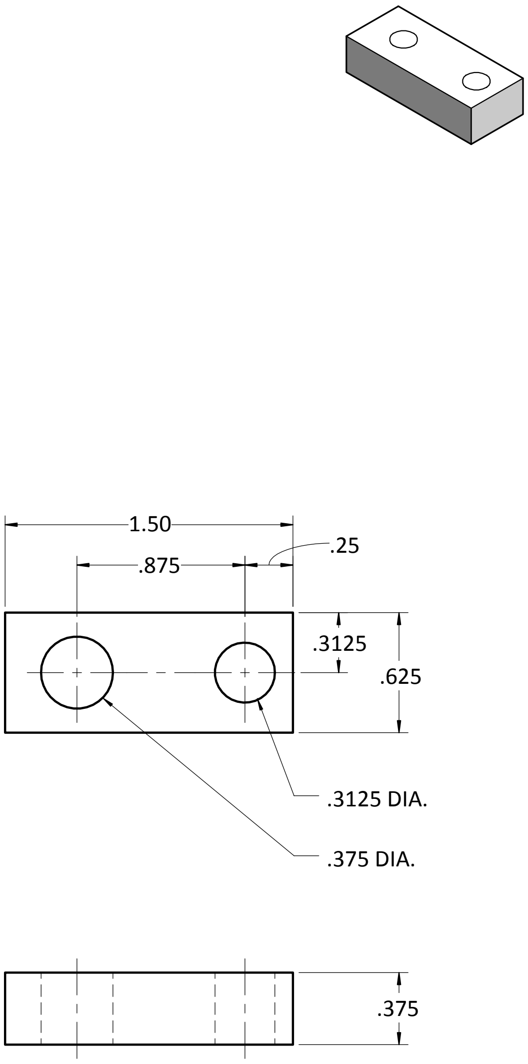
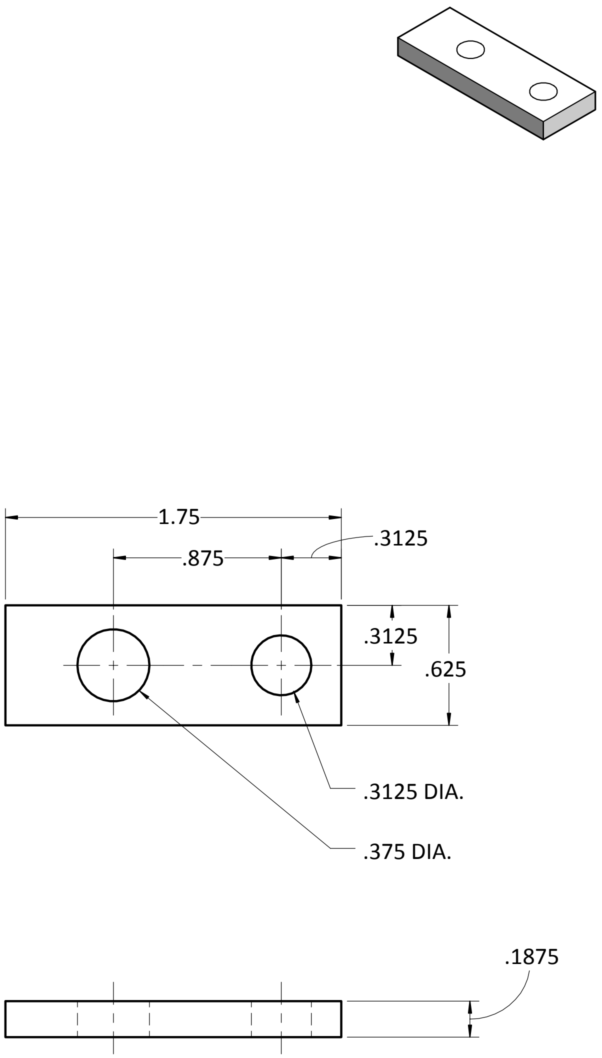
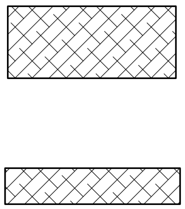
part # 3



PART # 4



PART # 5



material:
6061-T6 alum.

stock sizes:
.375 x 1.5
.1875 x 2.5

required: 1 (4)
2 (5)

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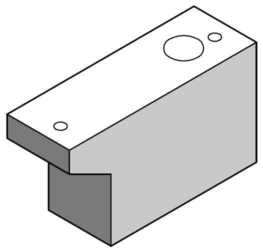
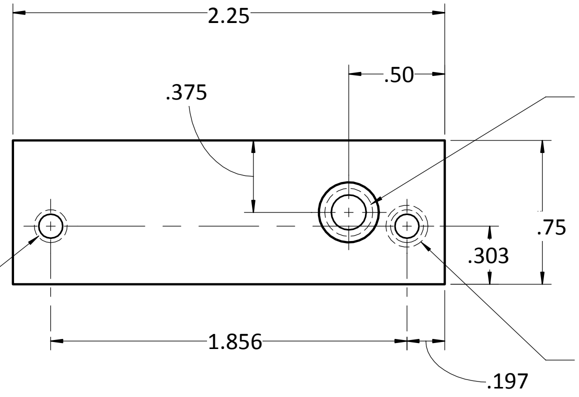
BENCHTOP CNC ROUTER PLANS

version 1.2

part #s 4,5

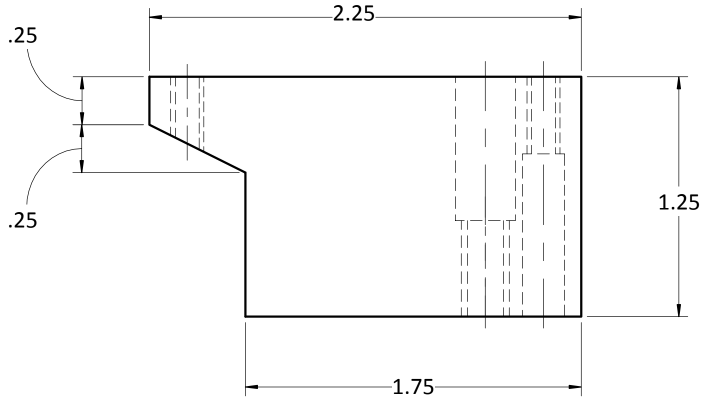




1/4-20 threaded, CBORE .3125 x .75 DP.

10-32 threaded

10-32 threaded, CBORE .25 DIA. x .875 DP.



material:
6061-T6 alum.

stock size:
.75 x 1.25

# required: 1

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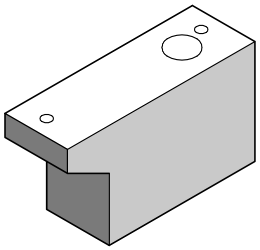
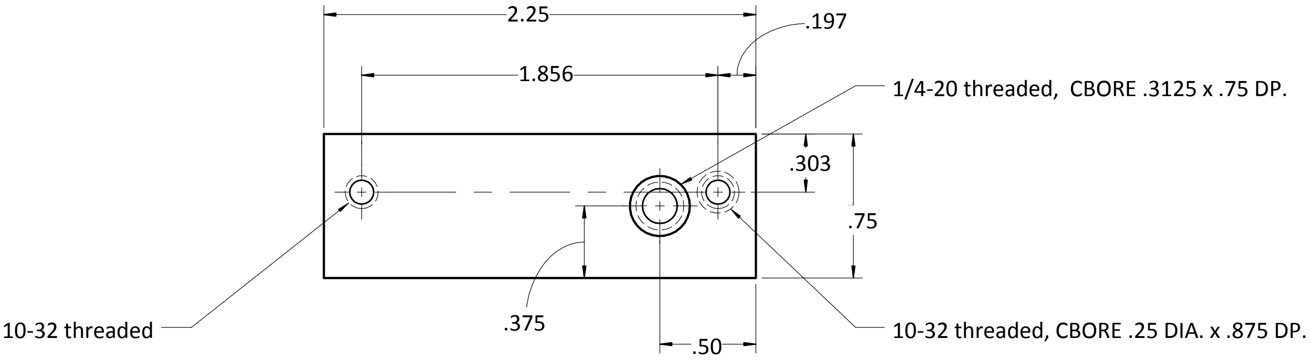
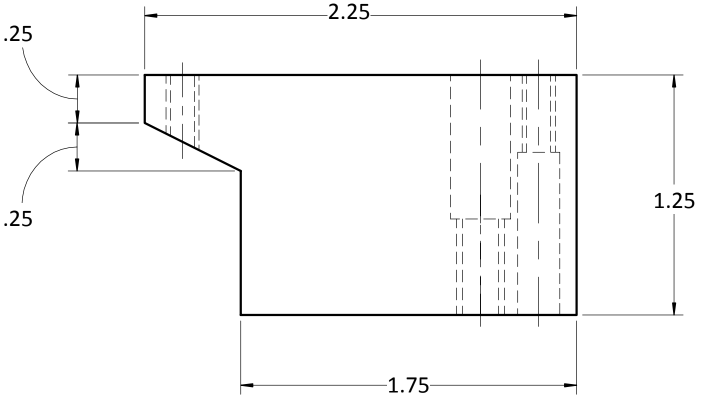
BENCHTOP CNC ROUTER PLANS

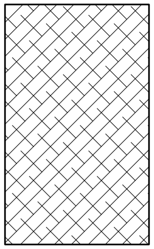
version 1.2

part # 6




2.25
1.856
.197
1/4-20 threaded, CBORE .3125 x .75 DP.
.303
.75
10-32 threaded
.375
.50
10-32 threaded, CBORE .25 DIA. x .875 DP.





material:
6061-T6 alum.

stock size:
.75 x 1.25

# required: 1

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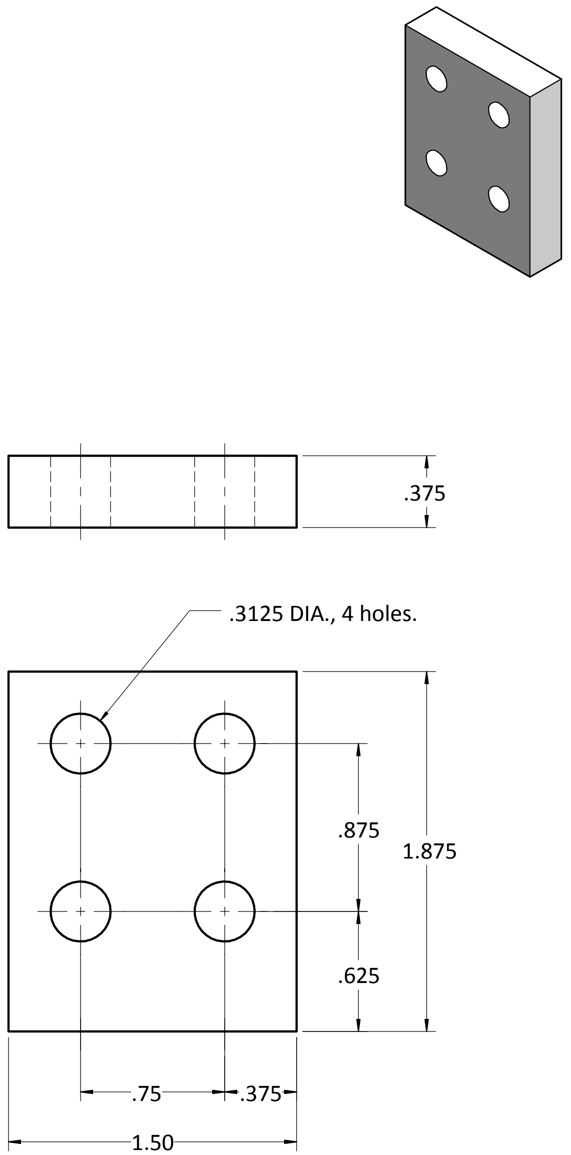
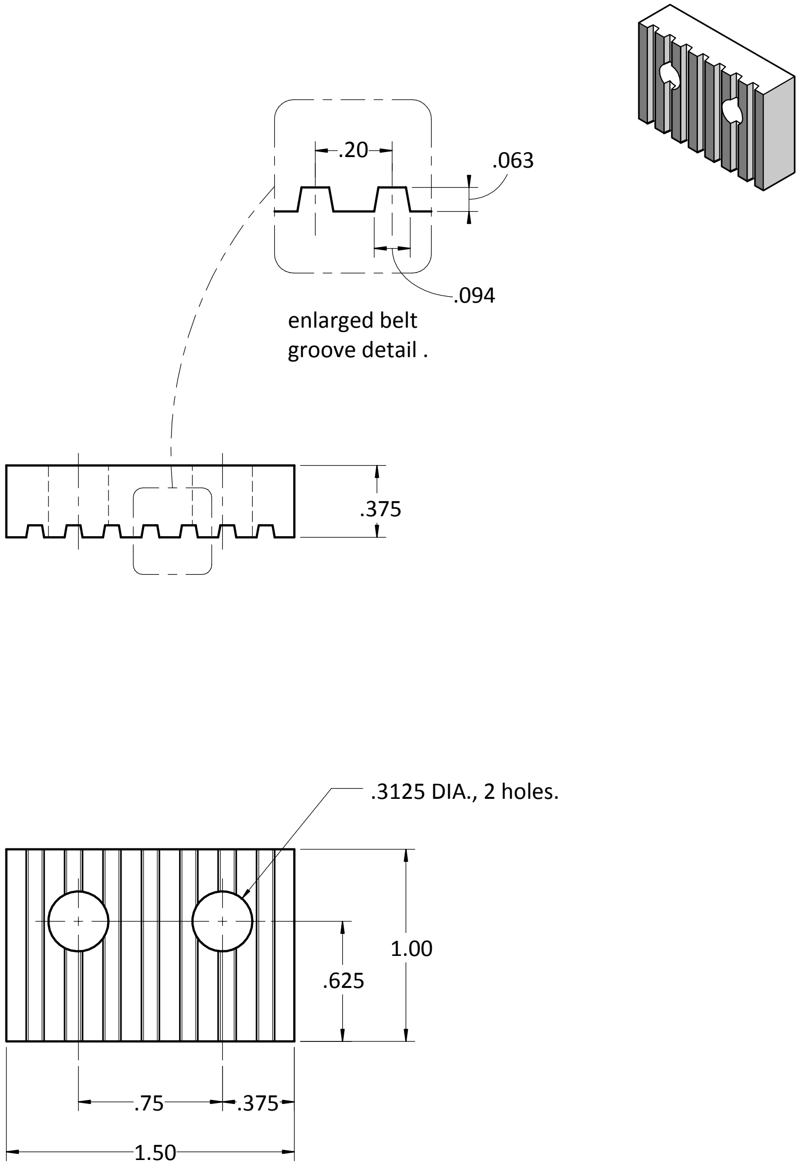
BENCHTOP CNC ROUTER PLANS

version 1.2

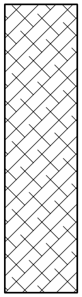
part # 7



PART # 8



PART # 9



material:
6061-T6 alum.

stock size:
.375 x 1.5

required: 1 ea.

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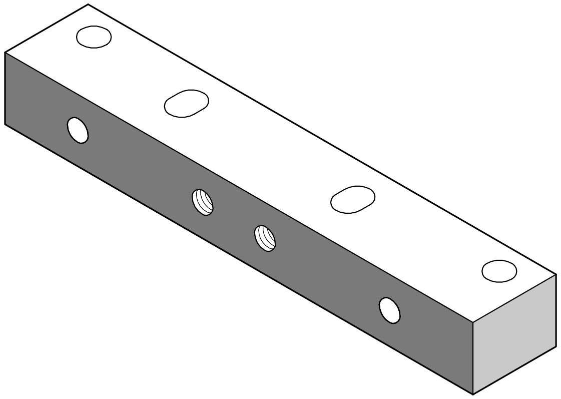
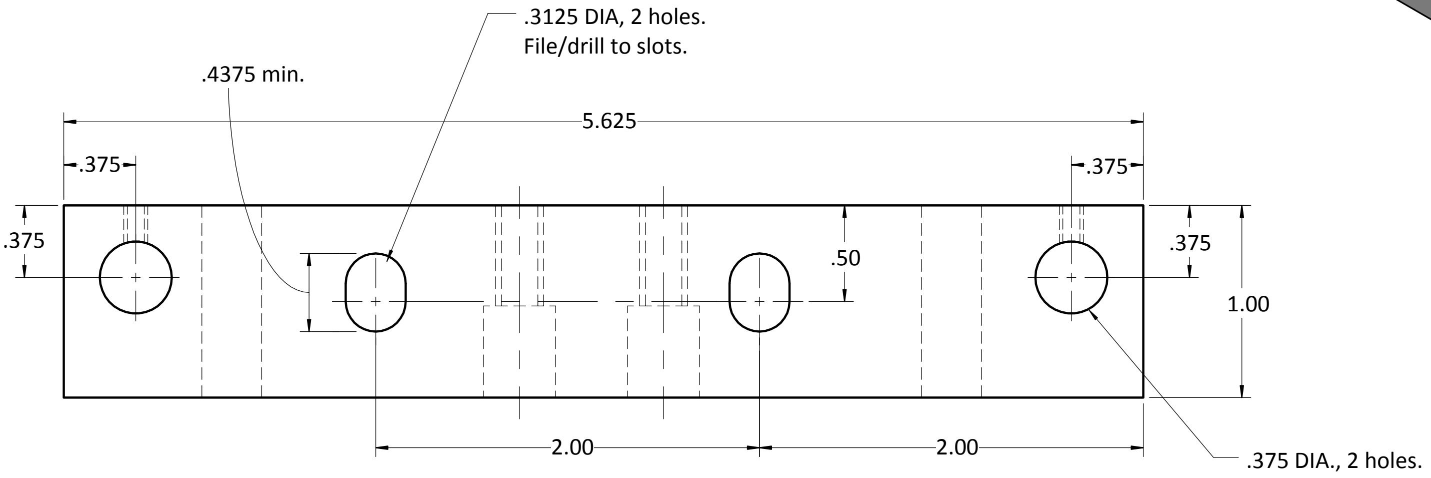
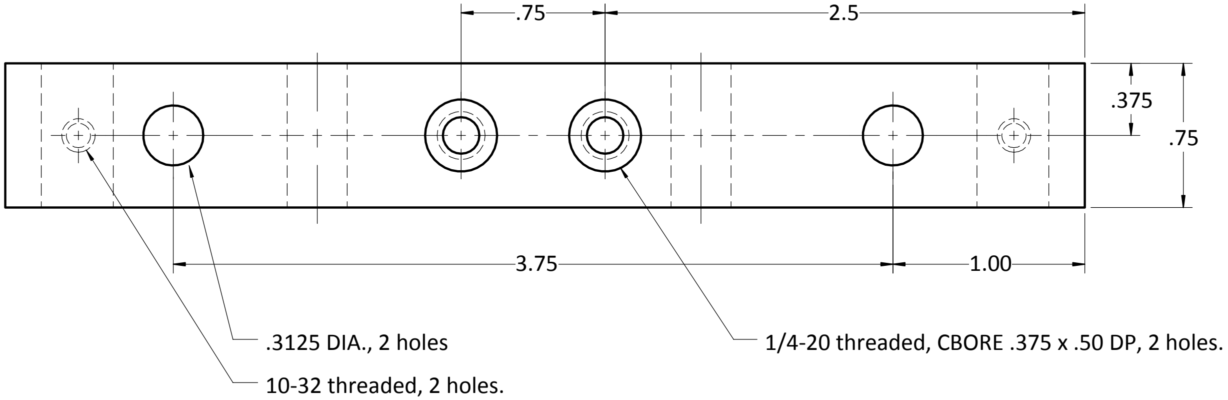
BENCHTOP CNC ROUTER PLANS

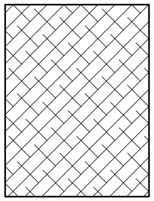
version 1.2

part #s 8,9









material:
6061-T6 alum.

stock size:
.75 x 1.00

# required: 1

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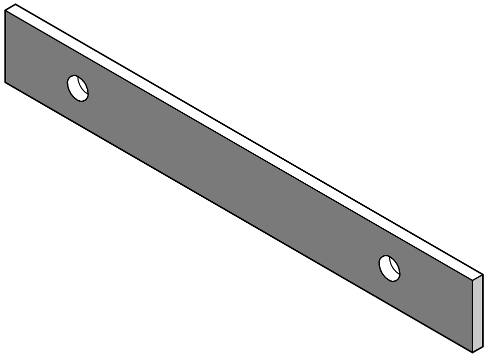
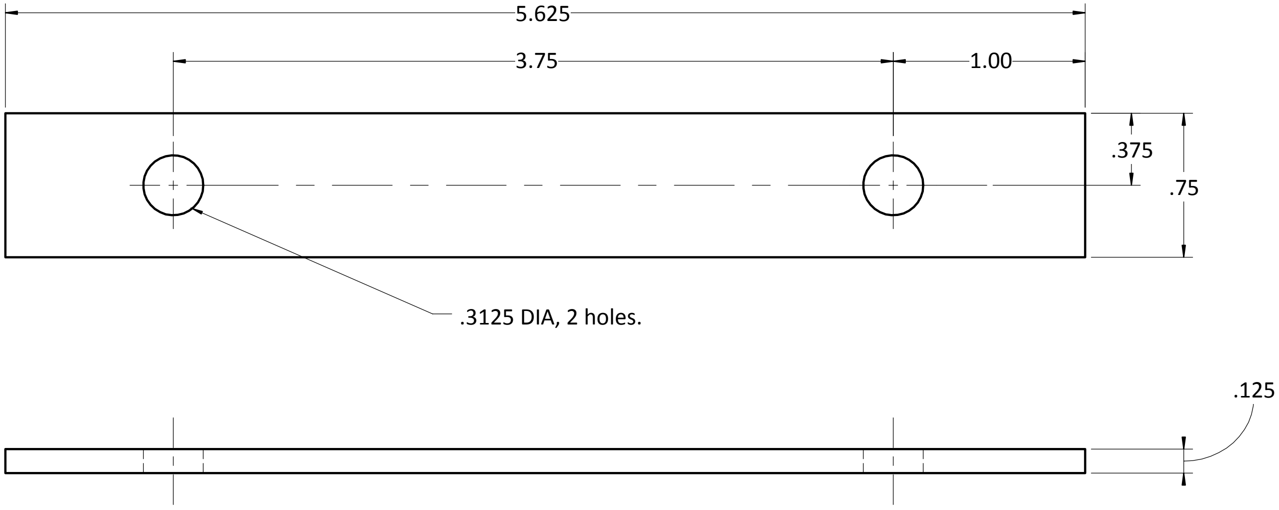
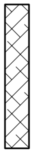
version 1.2

part # 10







material:
6061-T6 alum.

stock size:
.125 x .75

# required: 1

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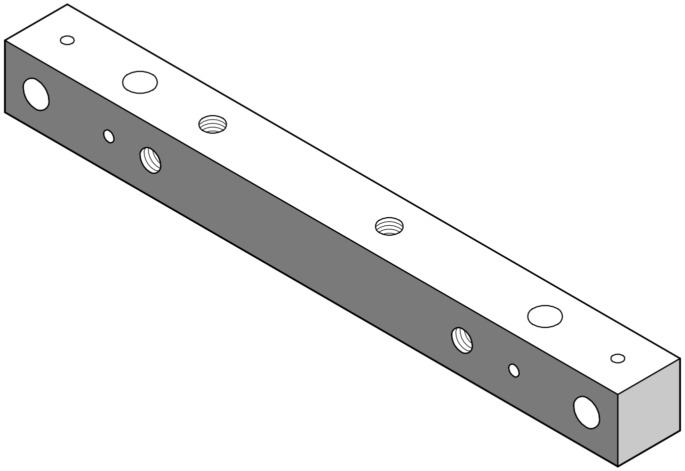
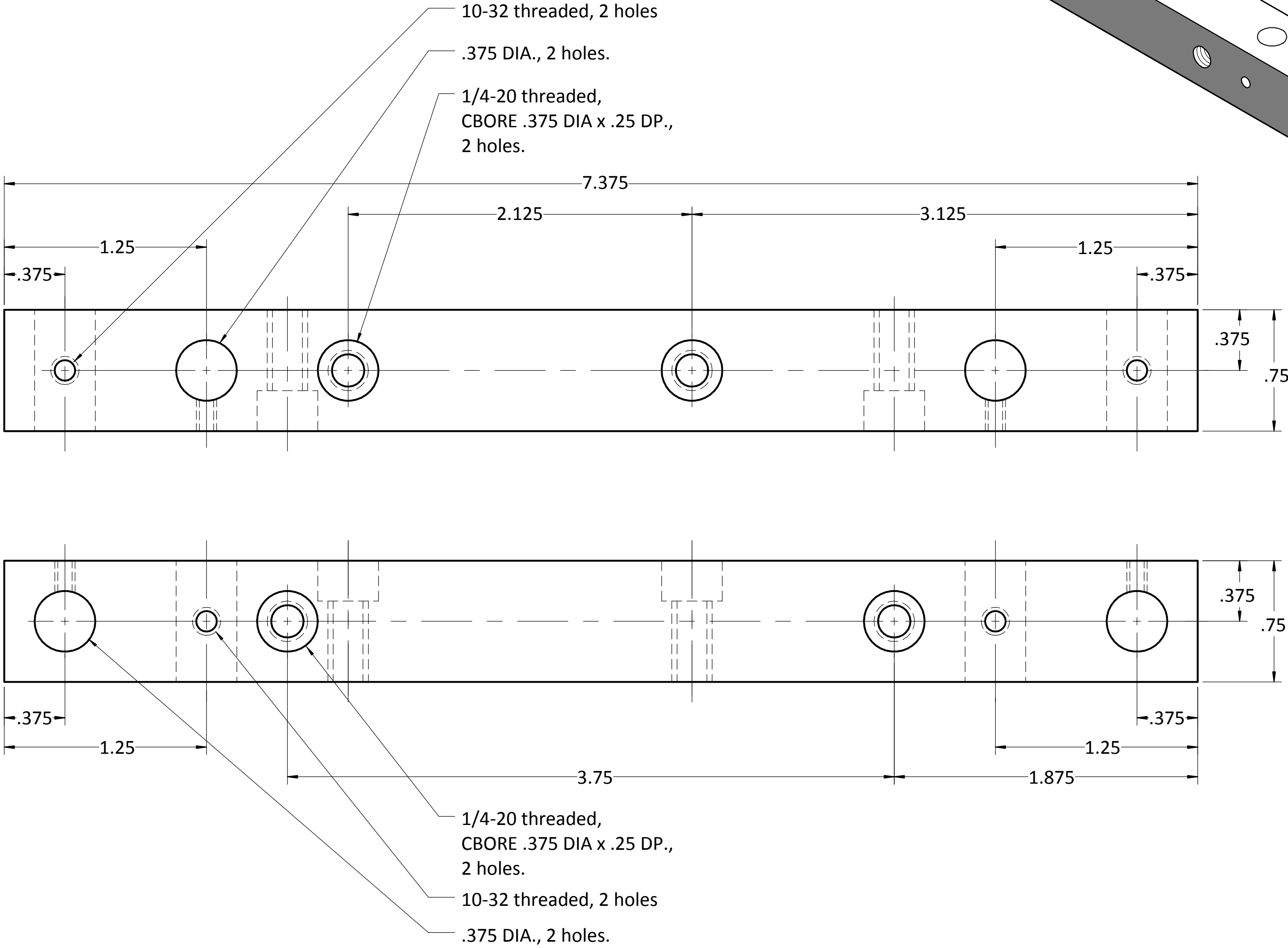
part # 11





▨

material:
6061-T6 alum.

stock size:
.75 x .75

# required: 1

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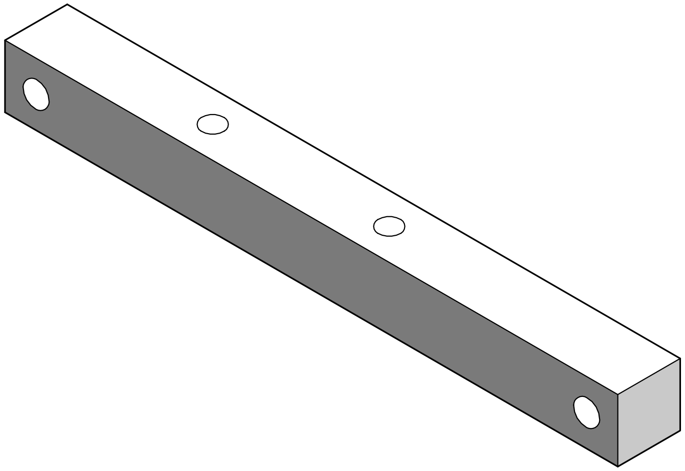
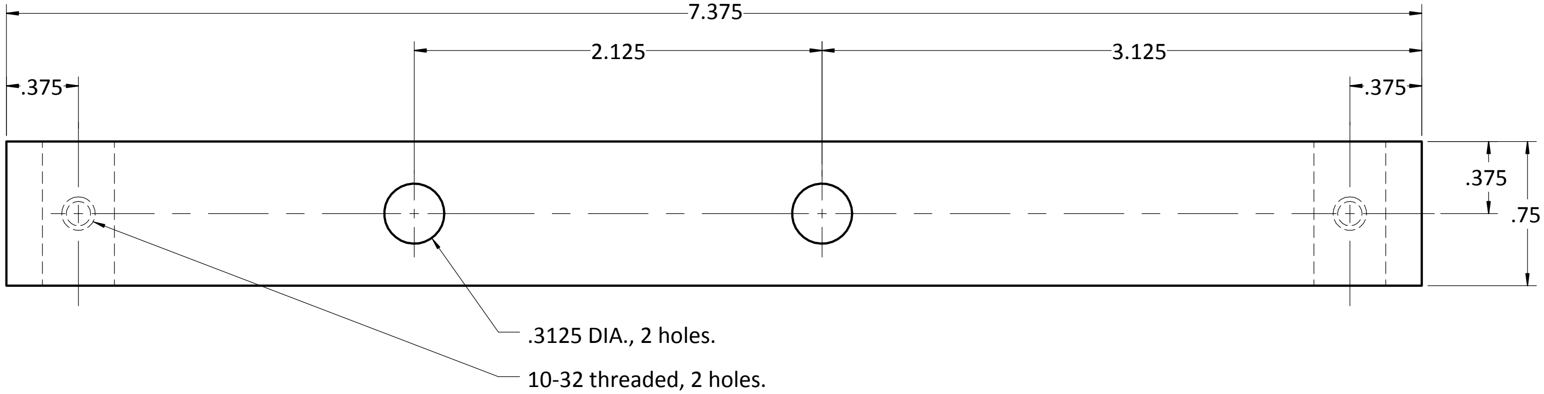
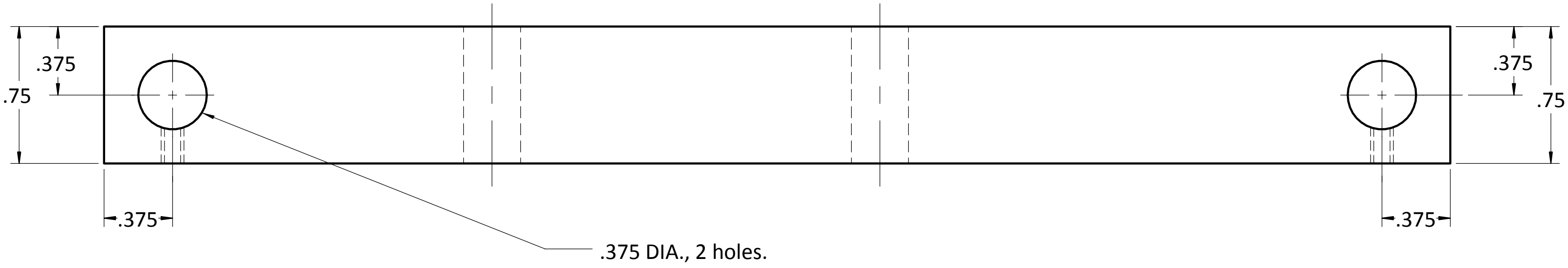
part # 12

12 gantry right top







▨

material:
6061-T6 alum.

stock size:
.75 x .75

# required: 1

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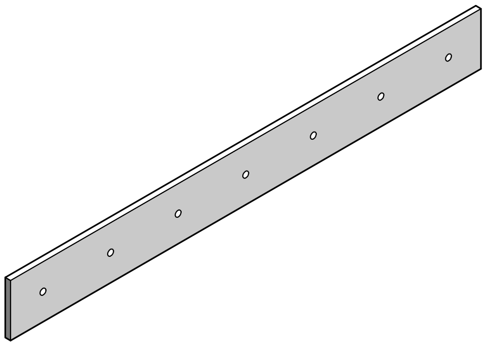
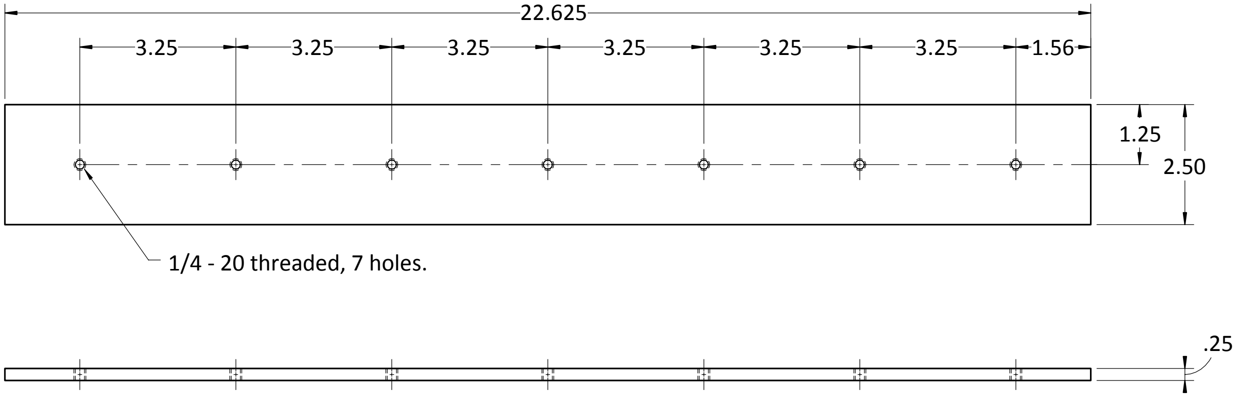
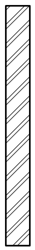
version 1.2

part # 13





1/4 - 20 threaded, 7 holes.



material:
1018
cold rolled steel

stock size:
.25 x .2.50

# required: 1

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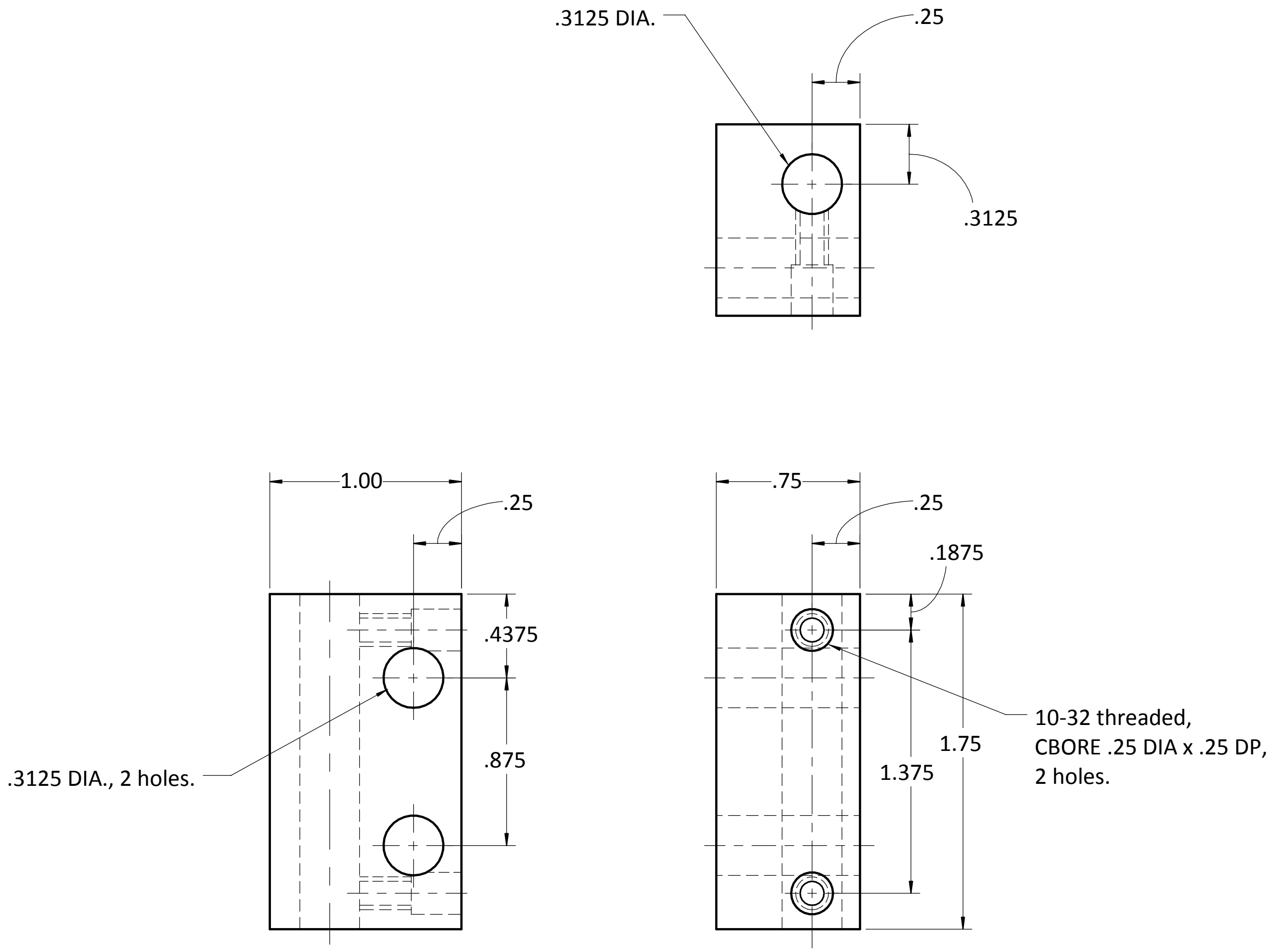
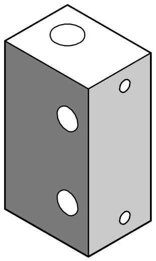
part # 14





▨

material:
6061-T6 alum.

stock size:
.75 x 1.00

# required: 3

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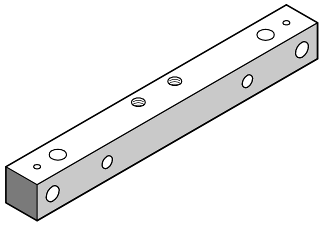
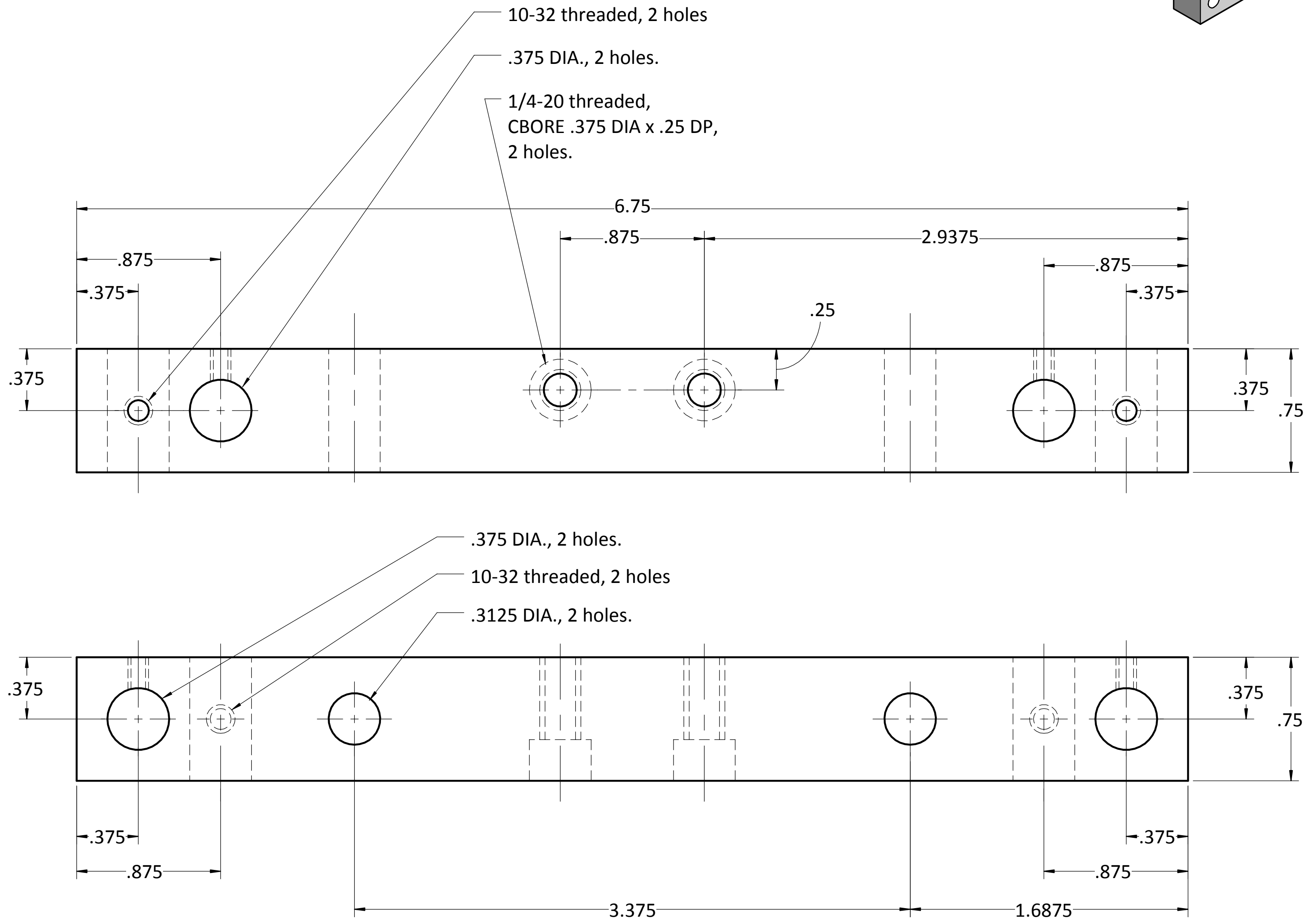
BENCHTOP CNC ROUTER PLANS

version 1.2

part # 15





material:
6061-T6 alum.

stock size:
.75 x .75

# required: 2

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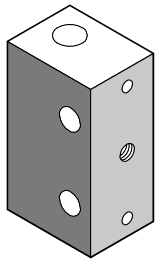
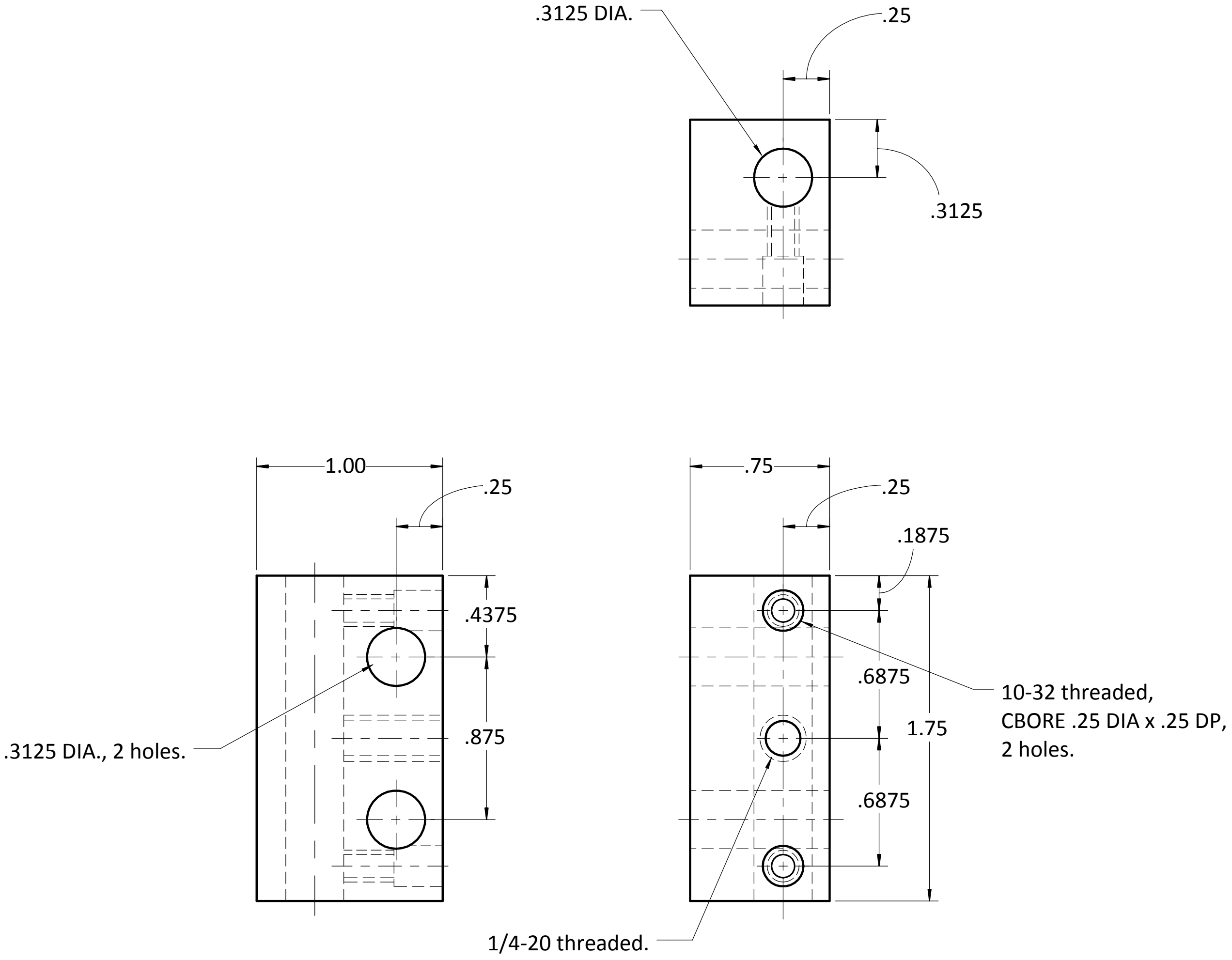
version 1.2

part # 16

16 carriage block rear





▨

material:
6061-T6 alum.

stock size:
.75 x 1.00

# required: 1

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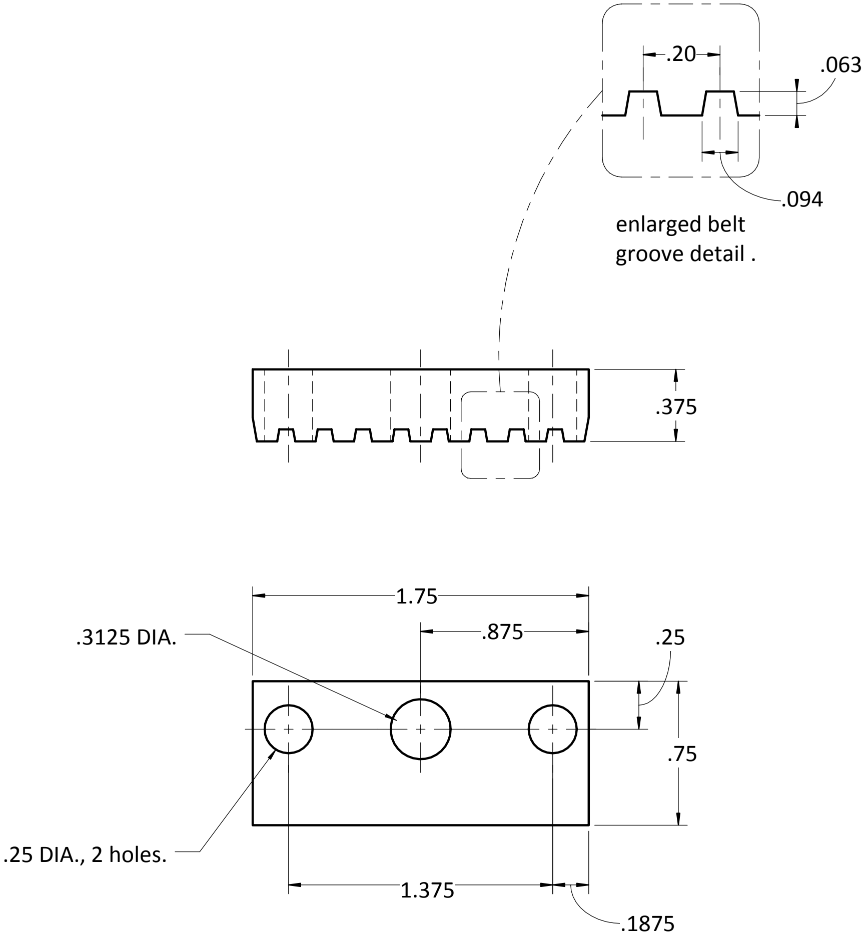
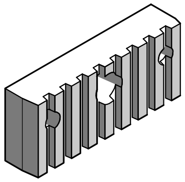
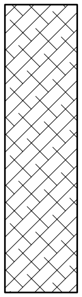
BENCHTOP CNC ROUTER PLANS

version 1.2

part # 17







material:
6061-T6 alum.

stock size:
.375 x 1.50

# required: 1

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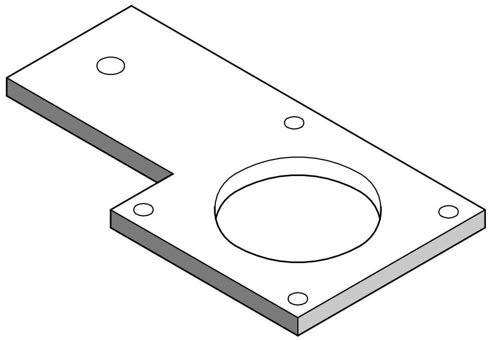
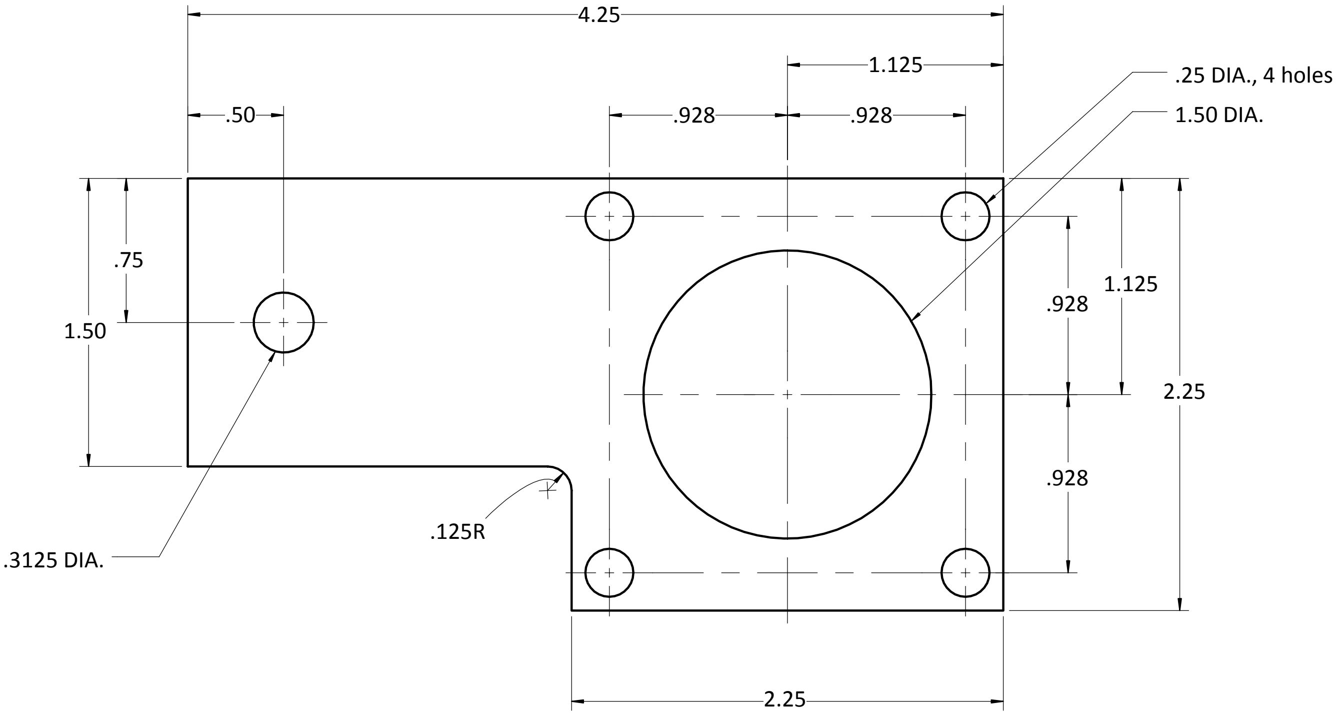
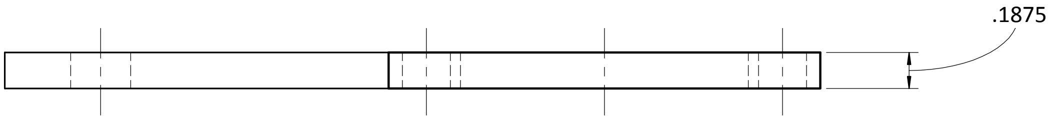
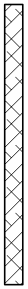
version 1.2

part # 18









material:
6061-T6 alum.

stock size:
.1875 x 2.5

# required: 1

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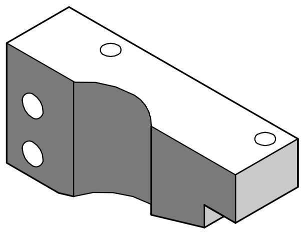
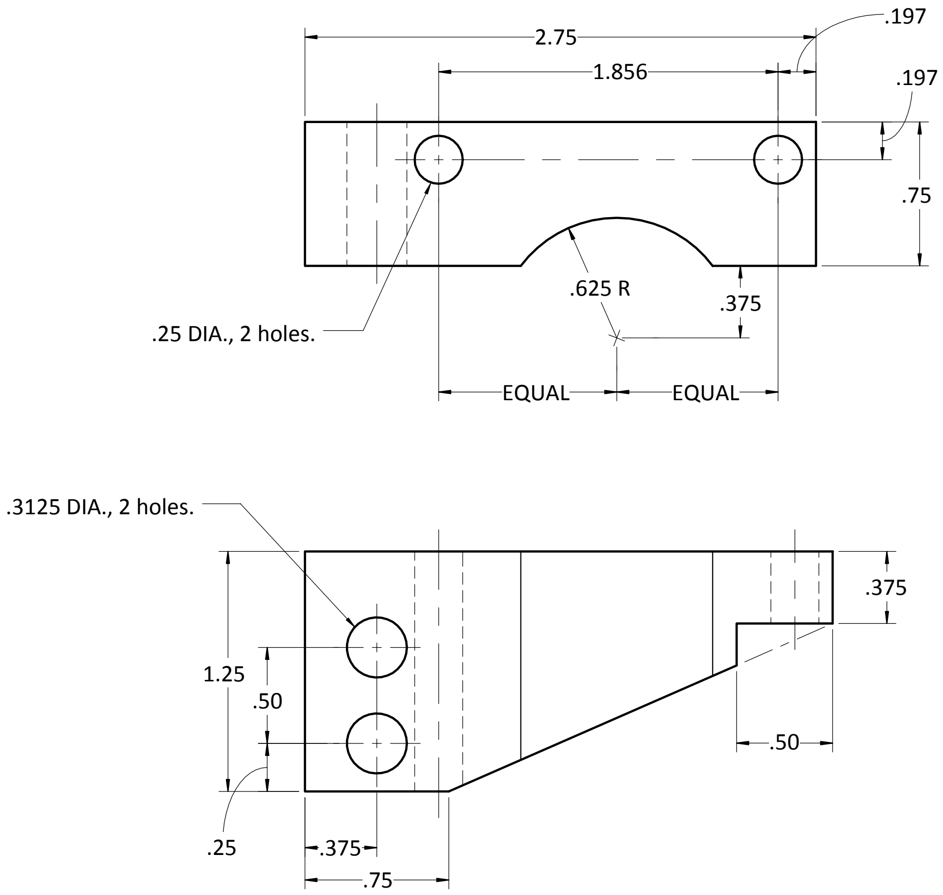
part # 19





material:
6061-T6 alum.

stock size:
.75 x 1.25

# required: 1

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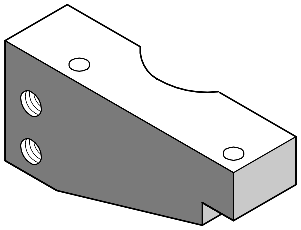
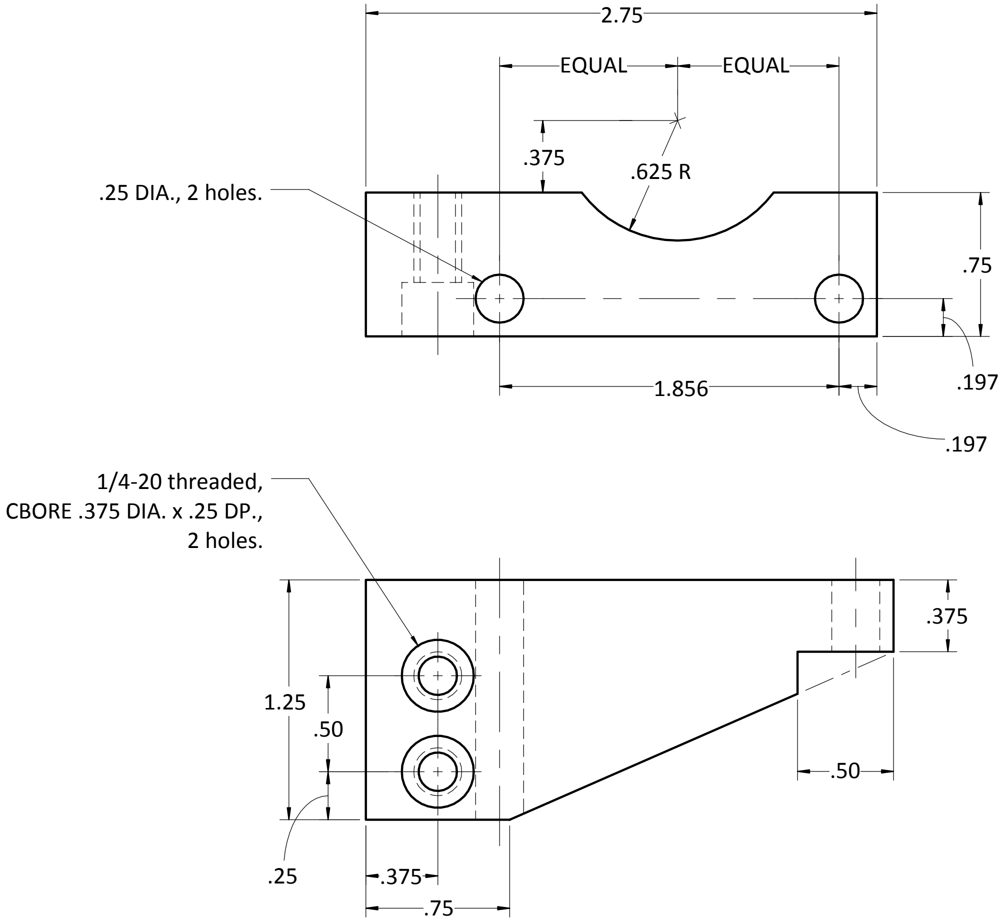
part # 20





material:
6061-T6 alum.

stock size:
.75 x 1.25

# required: 1

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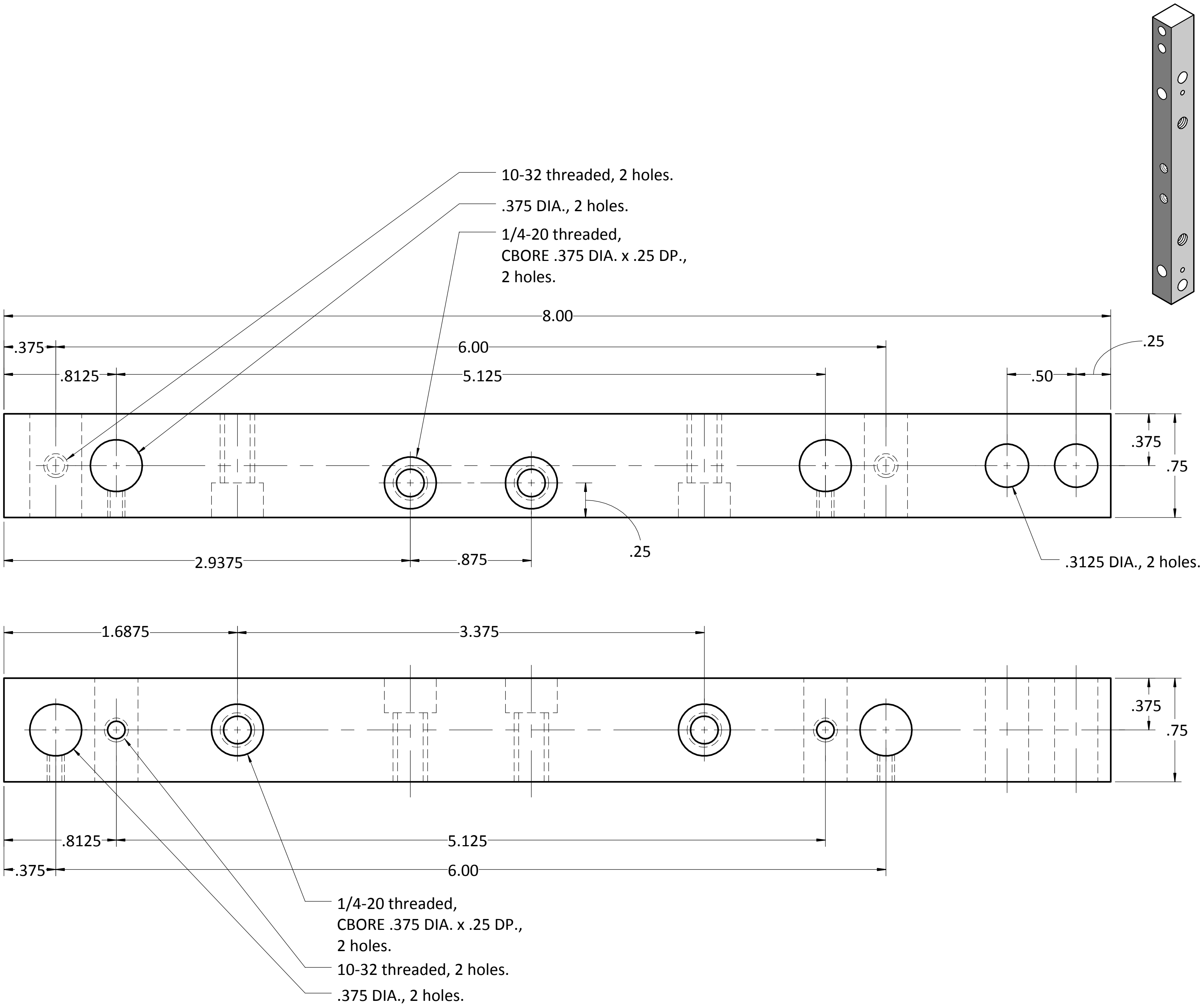
part # 21

21 Z motor mount left



material:
6061-T6 alum.

stock size:
.75 x .75

# required: 1

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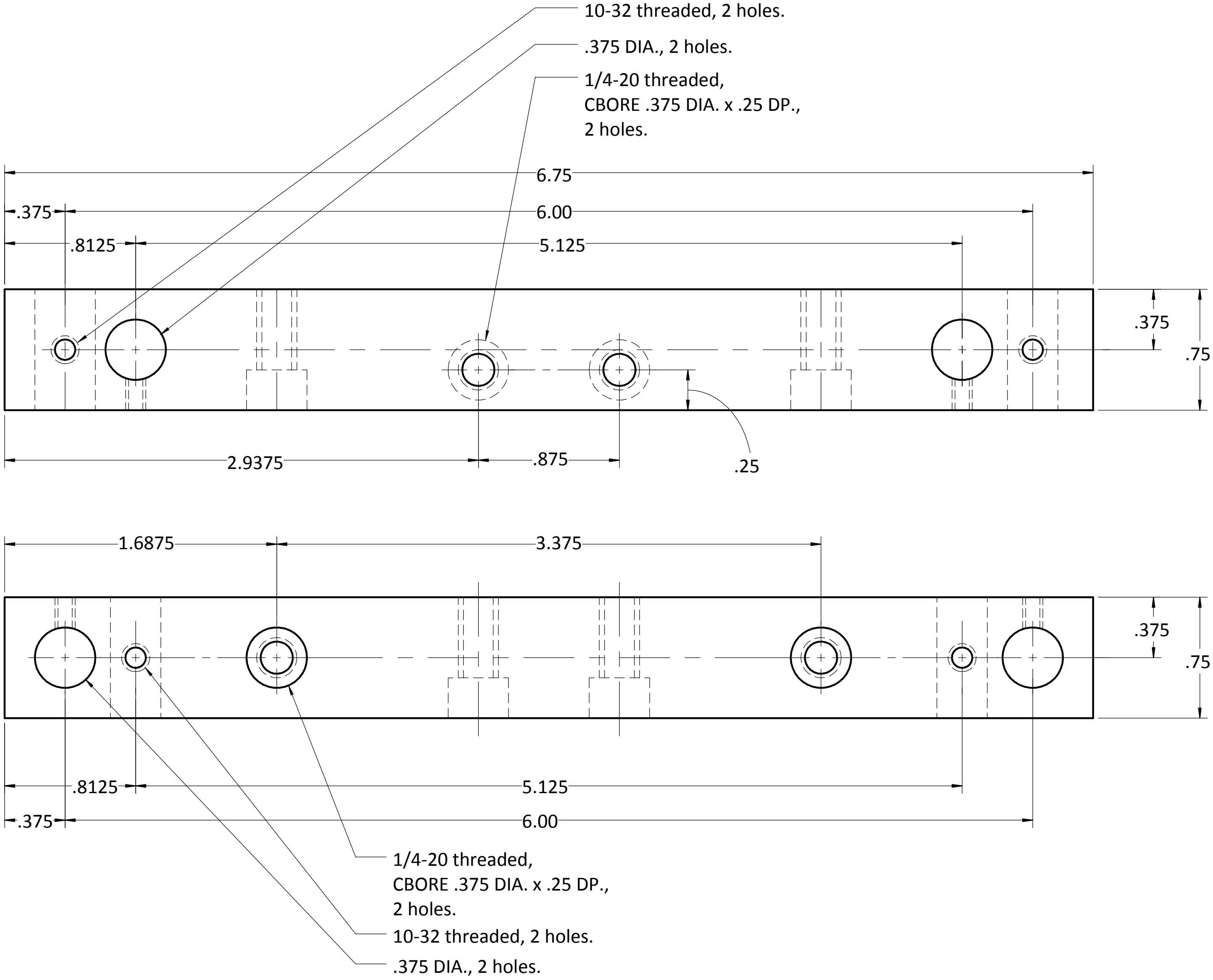
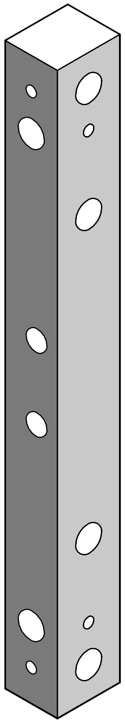
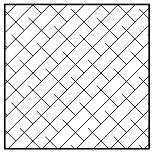
part # 22







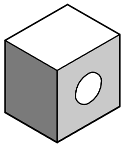
material:
6061-T6 alum.

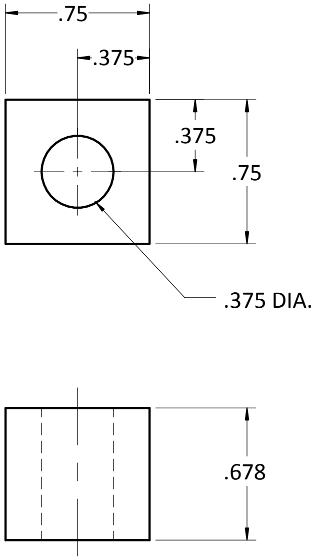
stock size:
.75 x .75

# required: 1

version 1.2

part # 23





NOTE:
It is critical that this thickness dimension be held as close as possible. Use of calipers or micrometer highly advised.

It is also crucial that this dimension is as consistent as possible between the 4 pieces.

▨

material:
6061-T6 alum.

stock size:
.75 x .75

# required: 4

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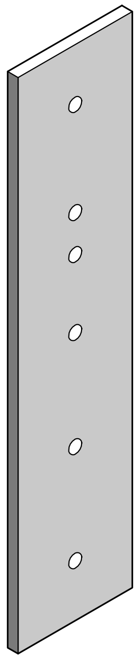
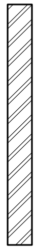
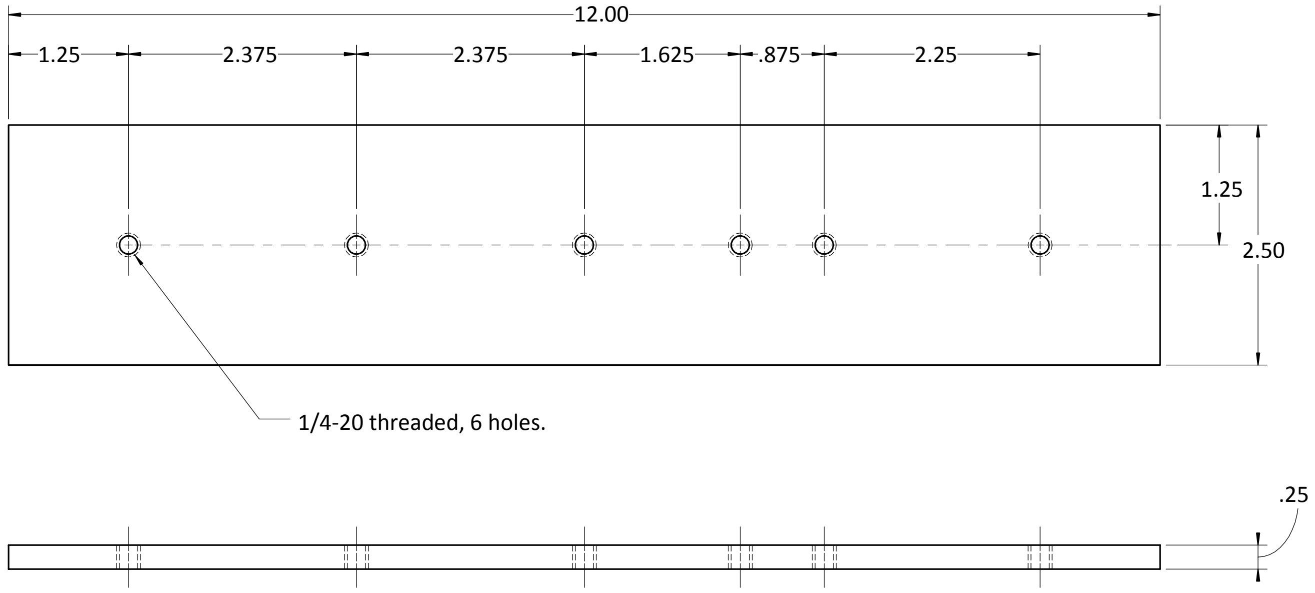
part # 24







material:
1018
cold rolled steel

stock size:
.25 x 2.50

# required: 1

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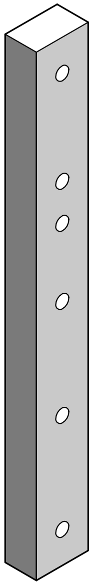
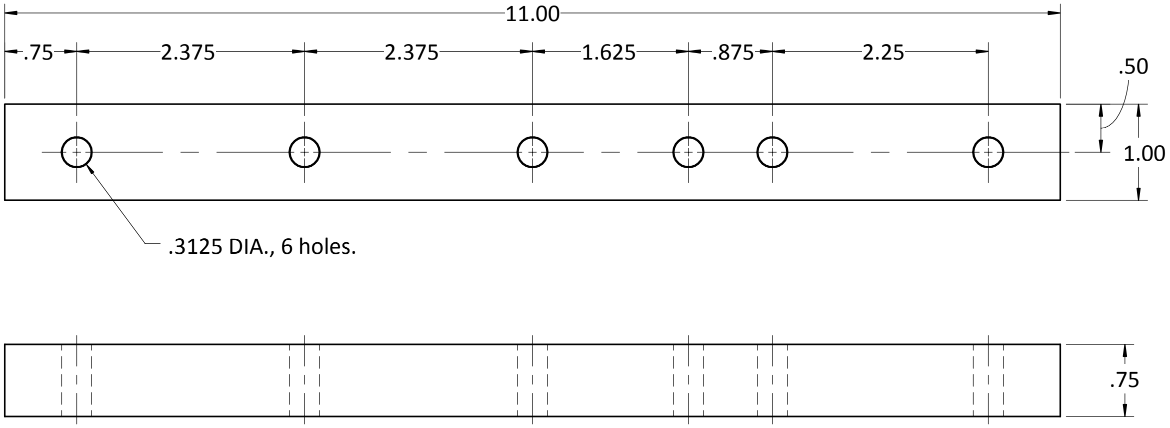
BENCHTOP CNC ROUTER PLANS

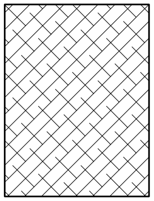
version 1.2

part # 25

25 Z rail







material:
6061-T6 alum.

stock size:
.75 x 1.00

# required: 1

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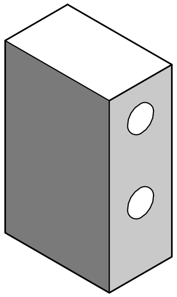
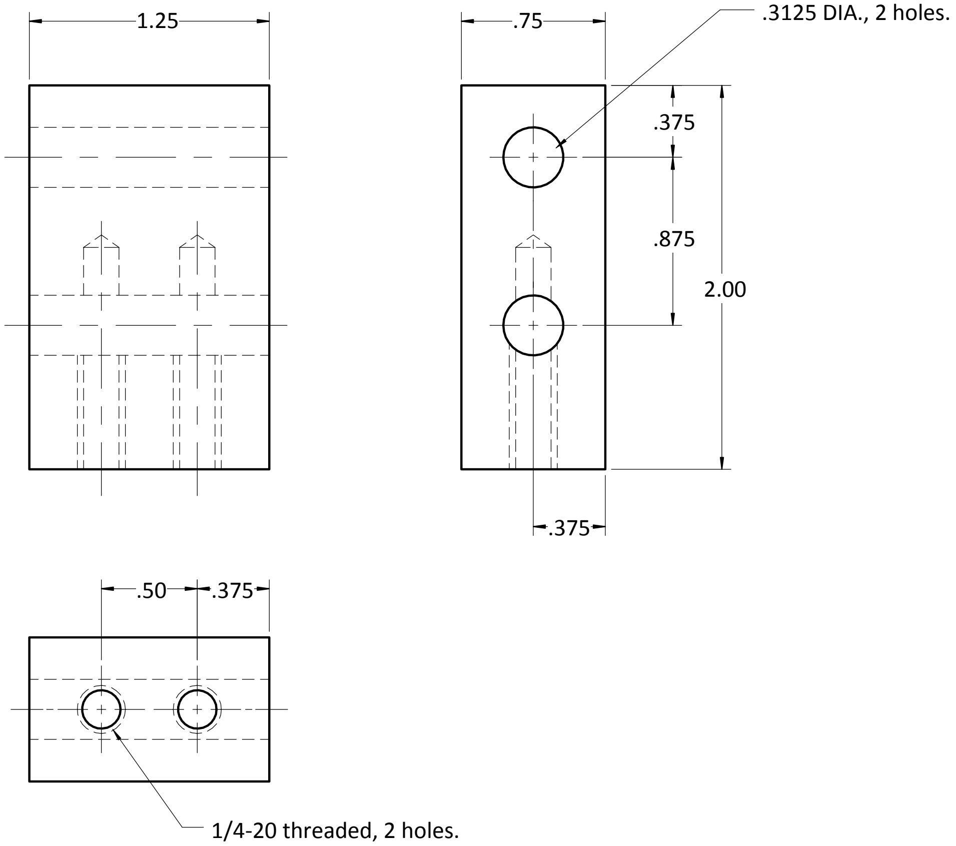
version 1.2

part # 26





material:
6061-T6 alum.

stock size:
.75 x 1.25

# required: 1

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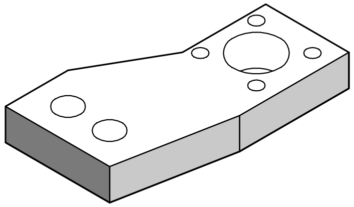
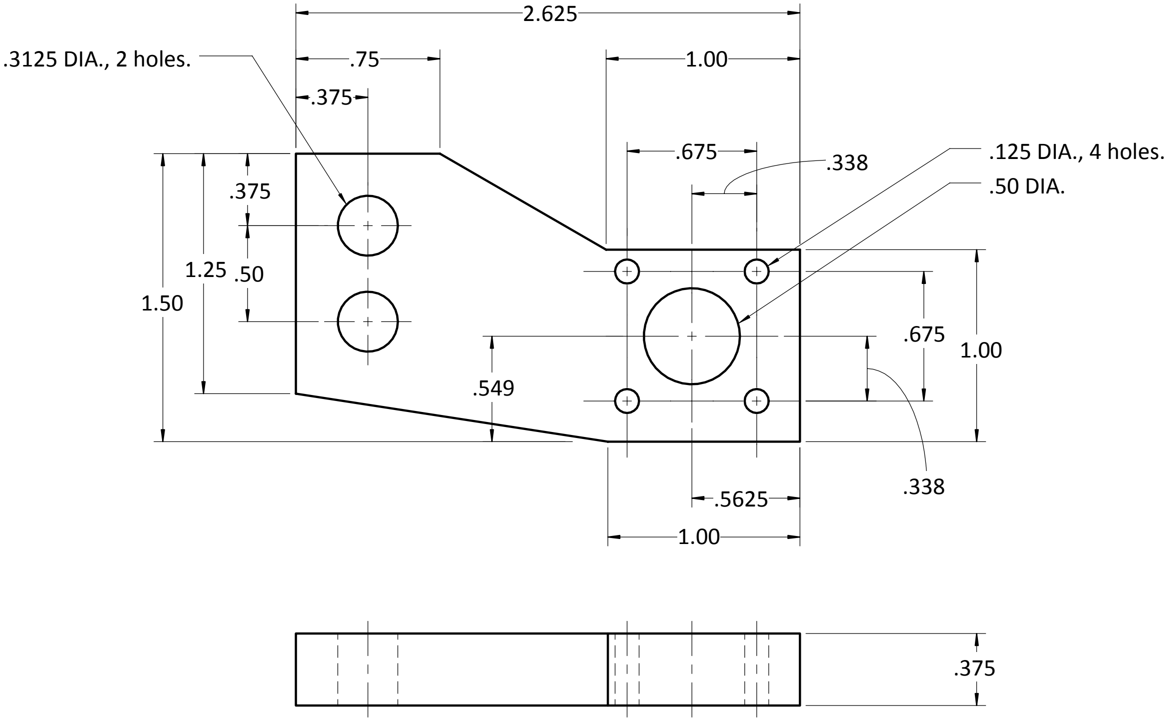
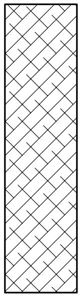
BENCHTOP CNC ROUTER PLANS

version 1.2

part # 27







material:
6061-T6 alum.

stock size:
.375 x 1.50

# required: 1

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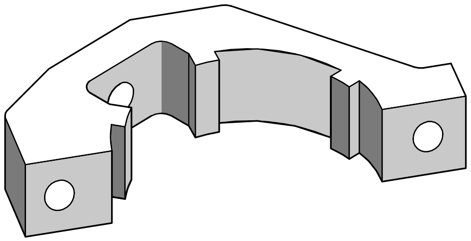
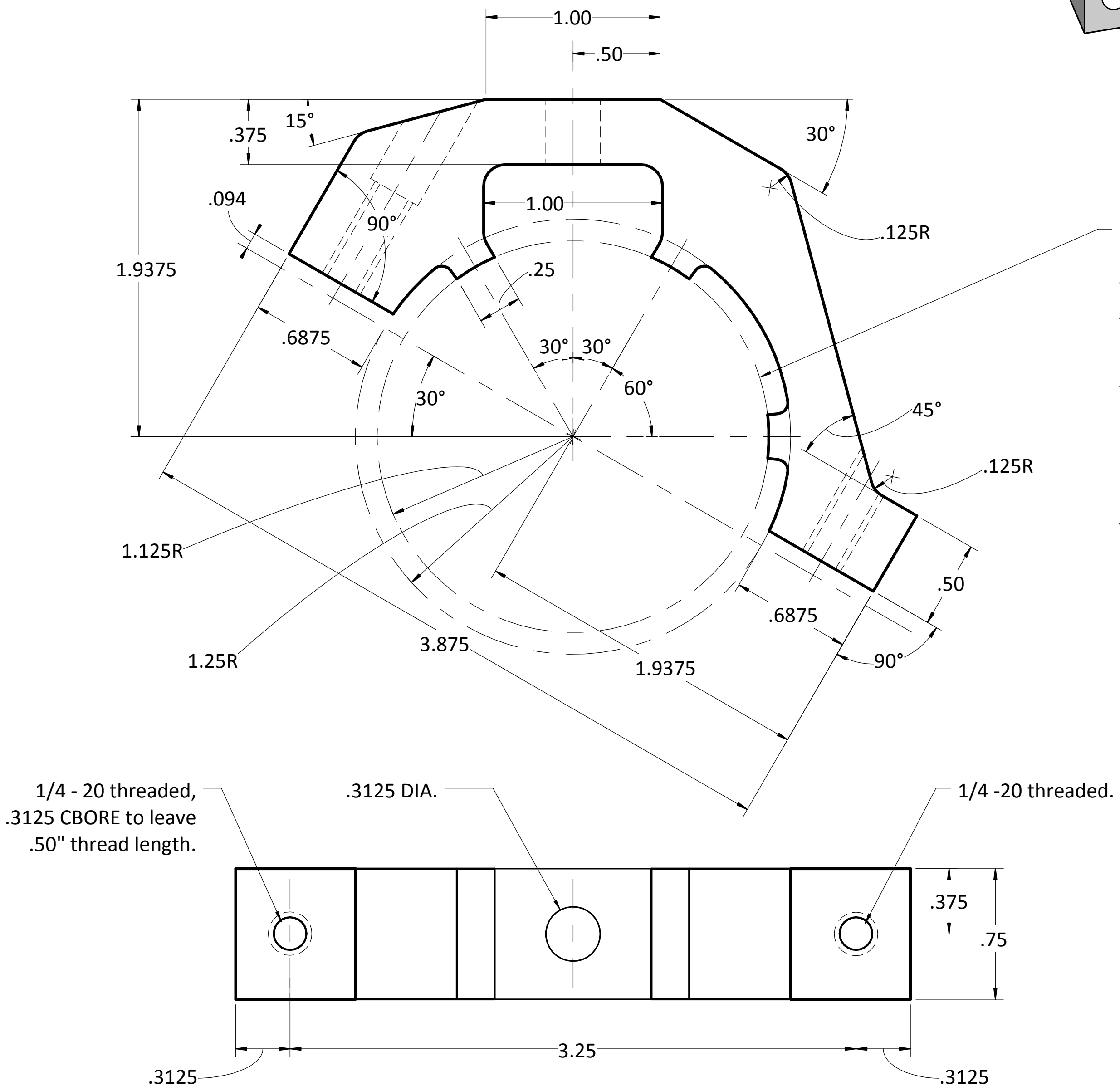
BENCHTOP CNC ROUTER PLANS

version 1.2

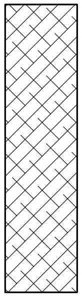
part # 28





NOTE:
Dimensions given are for a router with a body diamter of 2.25".
Adjust inner diameter as necessary if using a router of different size.

You may wish to fabricate the router mounts after the rest of the machine is constructed, in case any other changes need to be made to the design of these parts to accomodate your particular router.



material:
6061-T6 alum.

stock size:
.75 x 3.00

# required: 2

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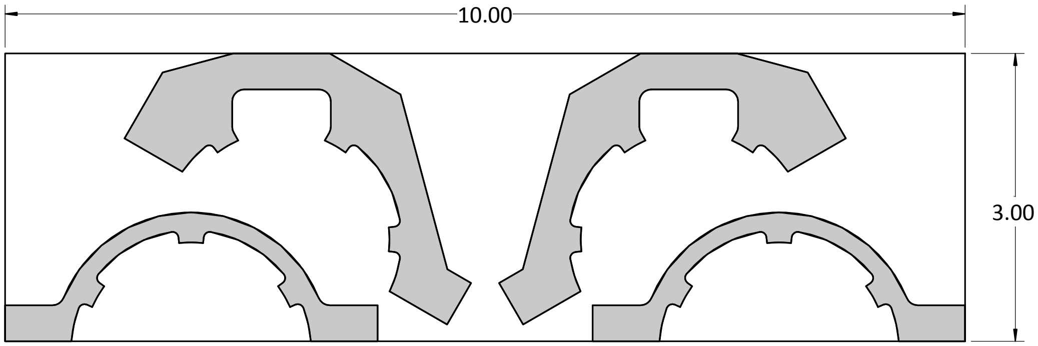
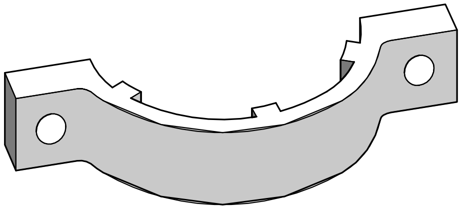
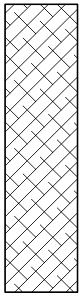
part # 29



Suggested layout of router mount and clamp parts on stock.

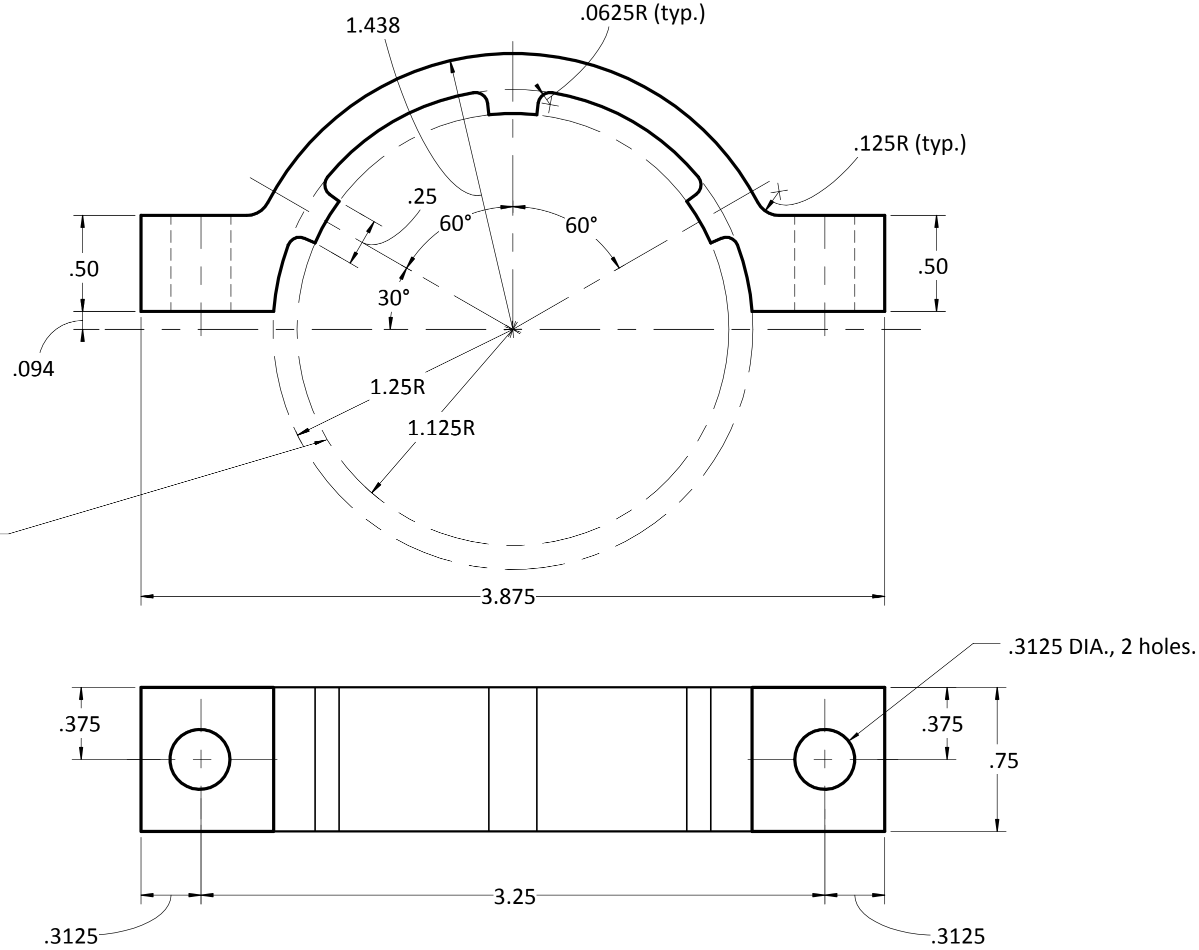




material:
6061-T6 alum.

stock size:
.75 x 3.00

# required: 2



NOTE:
Dimensions given are for a router with a body diamter of 2.25". Adjust inner diameter as necessary if using a router of different size.

You may wish to fabricate the router mounts and clamps after the rest of the machine is constructed, in case any other changes need to be made to the design of these parts to accomodate your particular router.

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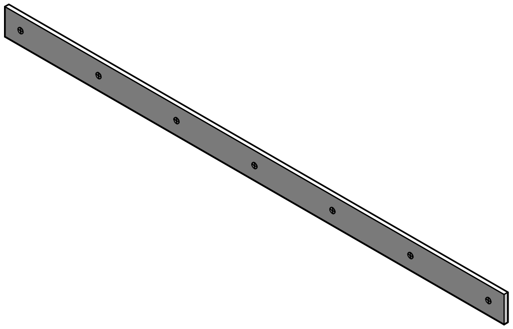
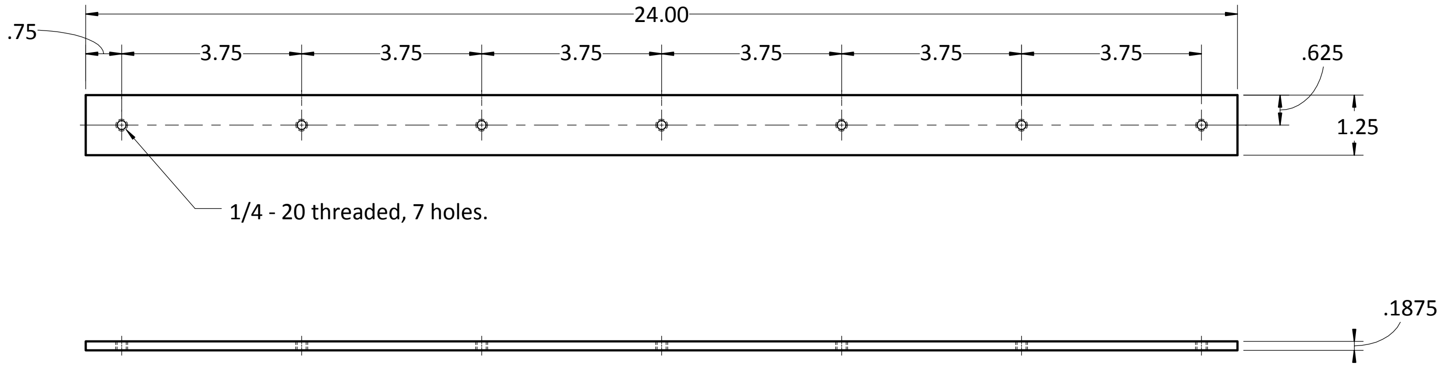
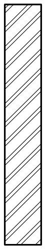
part # 30







material:
1018
cold rolled steel

stock size:
.1875 x 1.25

# required: 1

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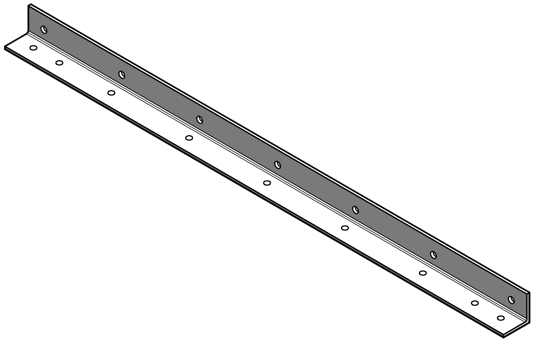
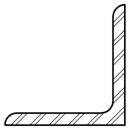
part # 31

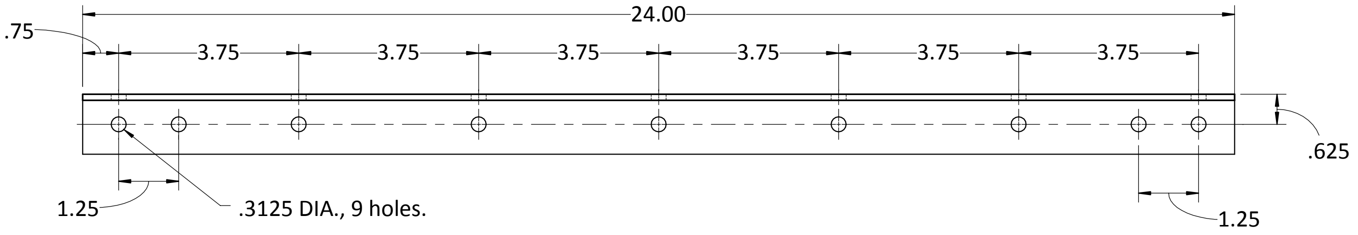


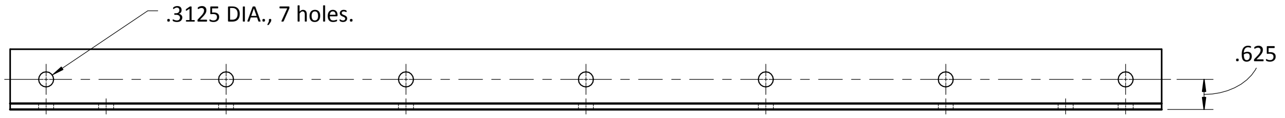


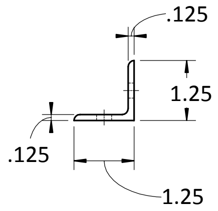
material:
A-36
hot rolled steel

stock size:
1.25 x 1.25 x .125

# required: 1







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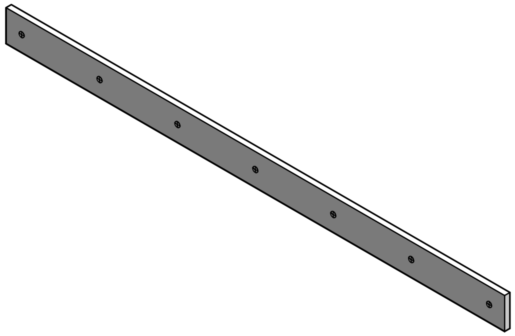
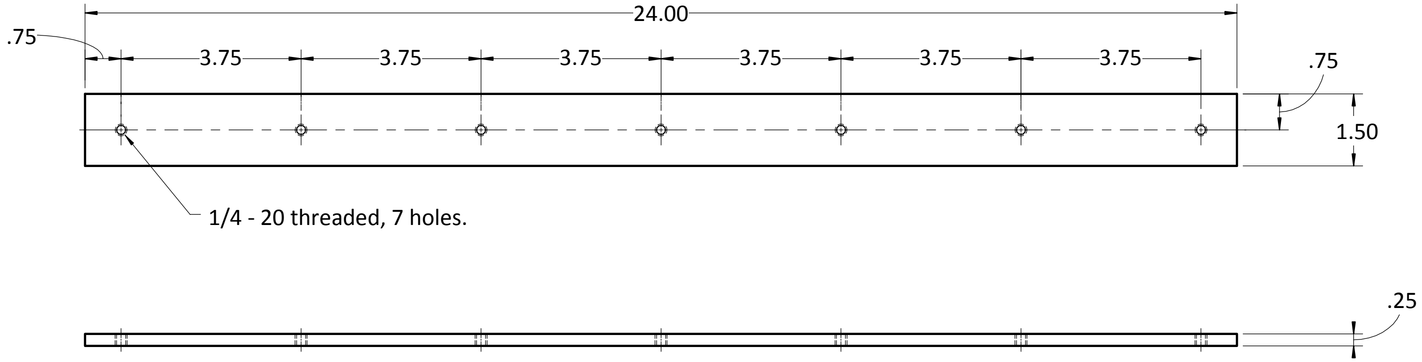
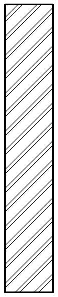
part # 32







material:
1018
cold rolled steel

stock size:
.25 x 1.50

# required: 1

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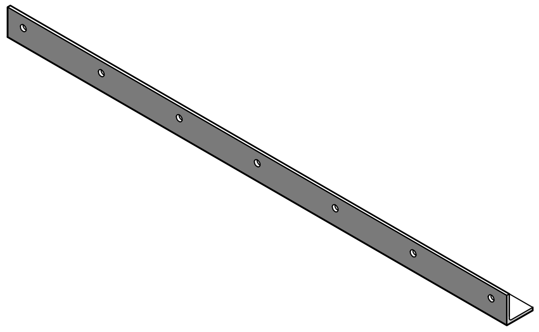
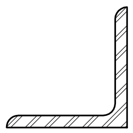
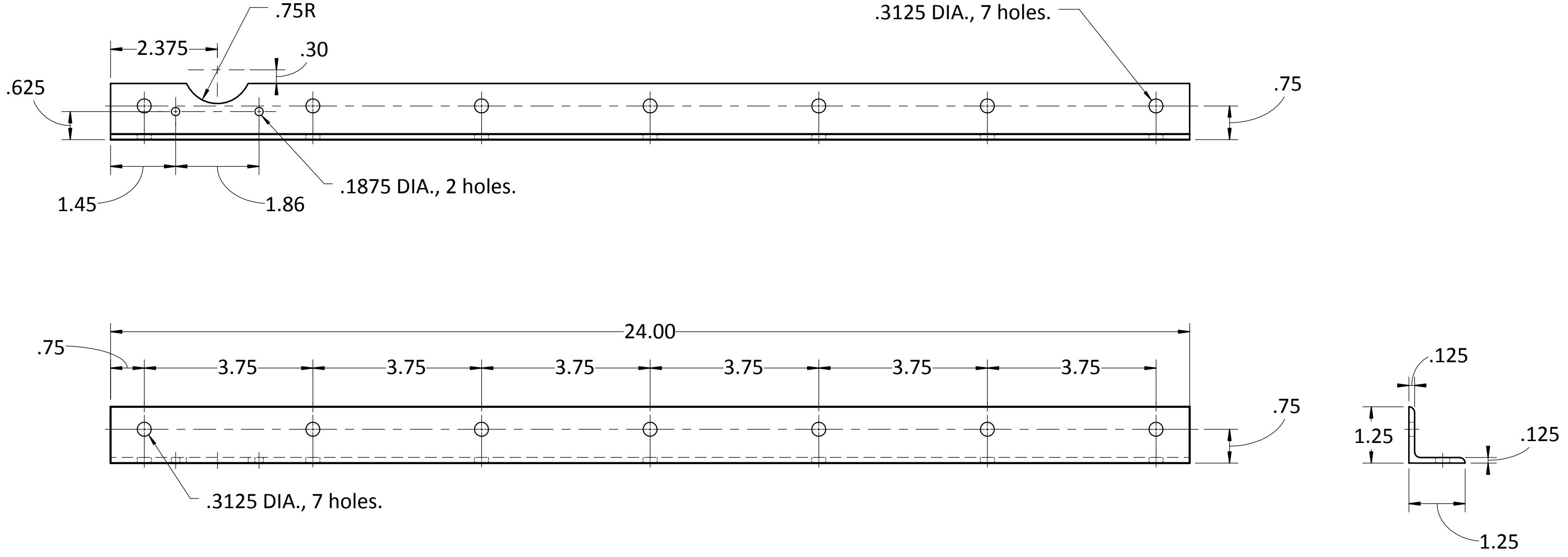
part # 33







material:
A-36
hot rolled steel

stock size:
1.25 x 1.25 x .125

# required: 1

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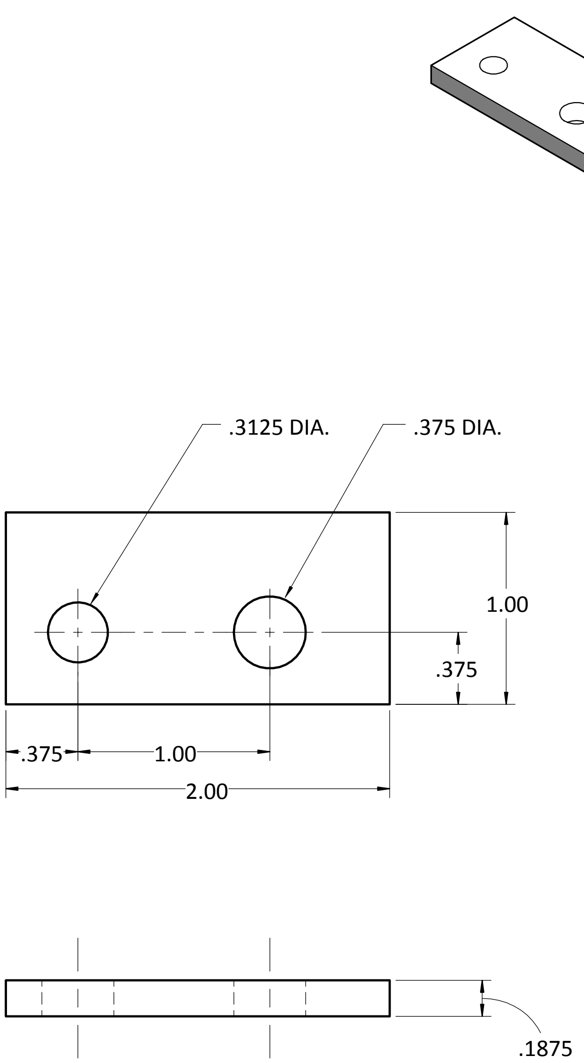
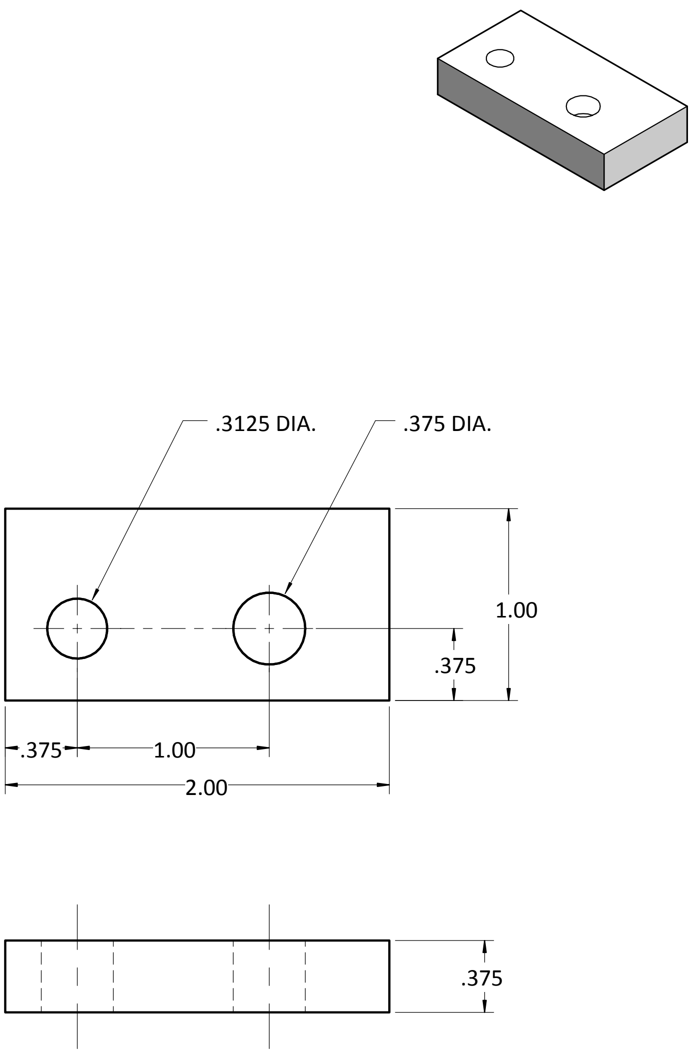
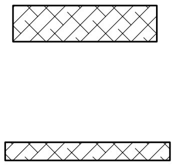
part # 34



PART # 35



PART # 36

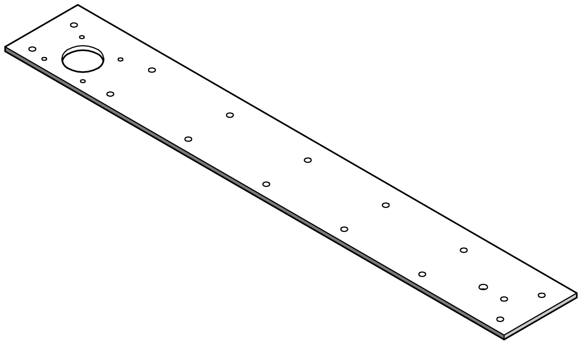


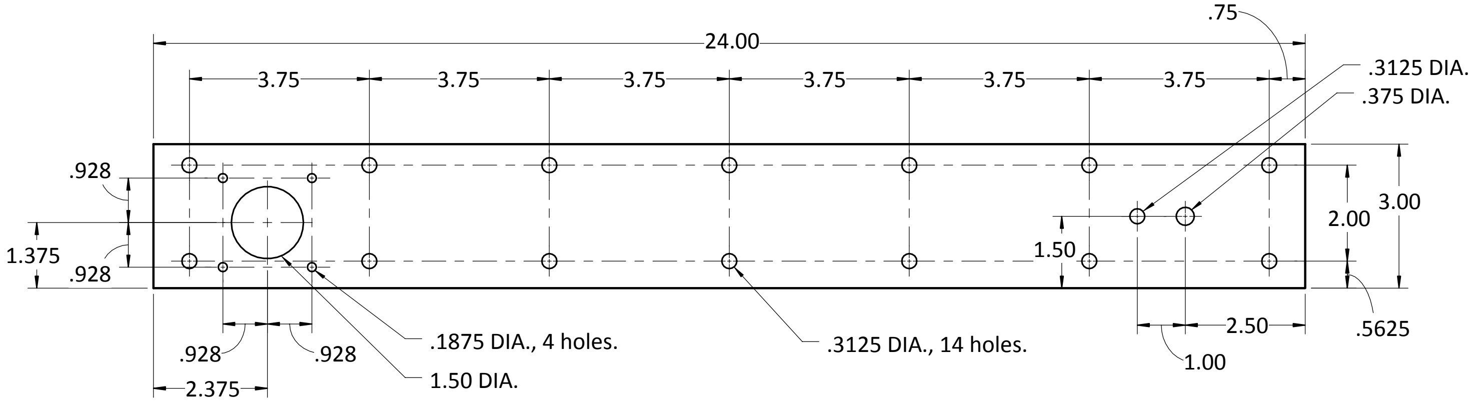
material:
6061-T6 alum.

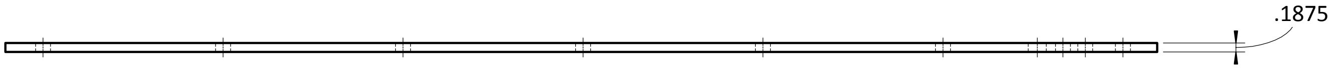
stock sizes:
.375 x 1.50
.1875 x 2.5

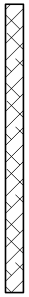
required: 1ea.

part #s 35,36









material:
6061-T6 alum.

stock size:
.1875 x 3.50

# required: 1

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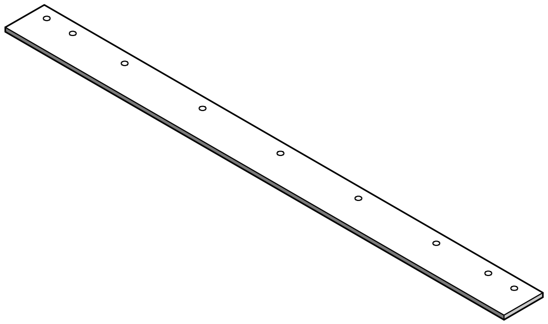
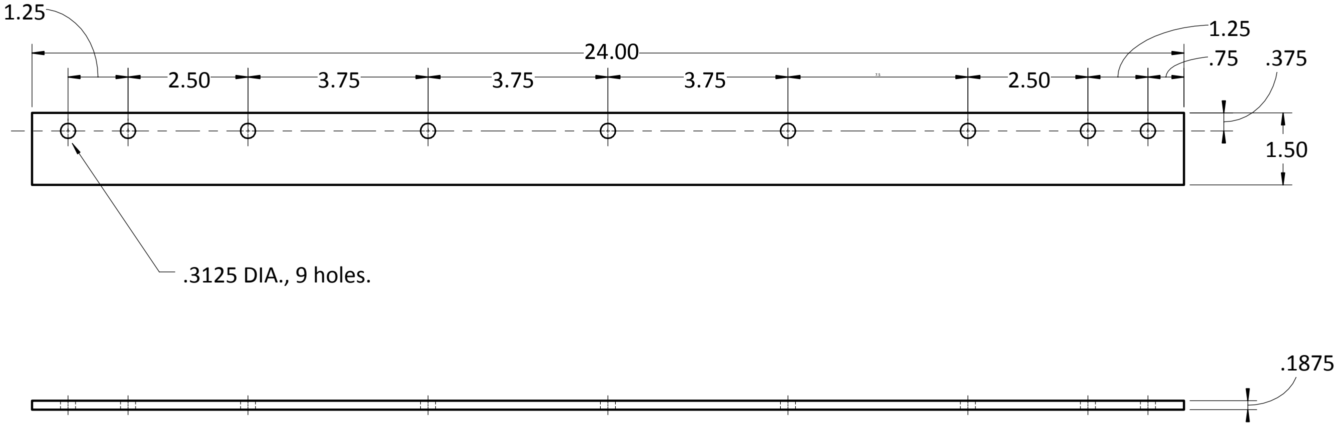
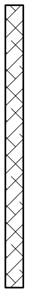
part # 37

37 X motor plate







material:
6061-T6 alum.

stock size:
.1875 x 2.00

# required: 1

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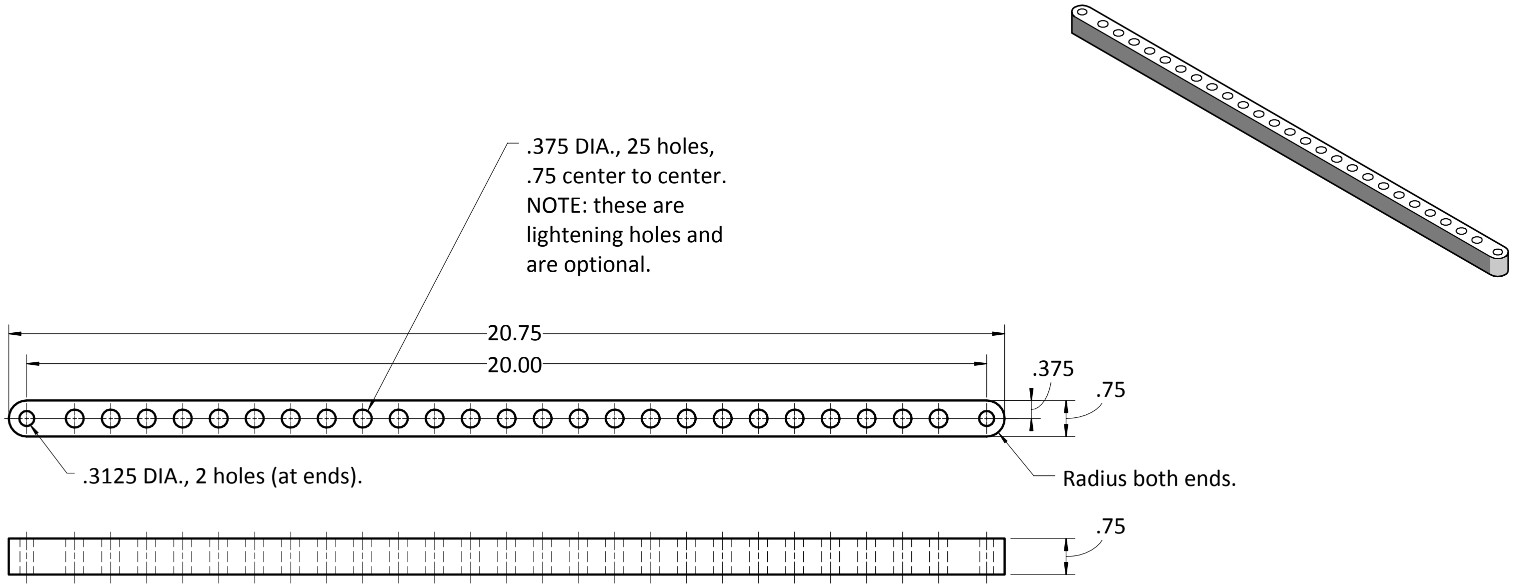
part # 38

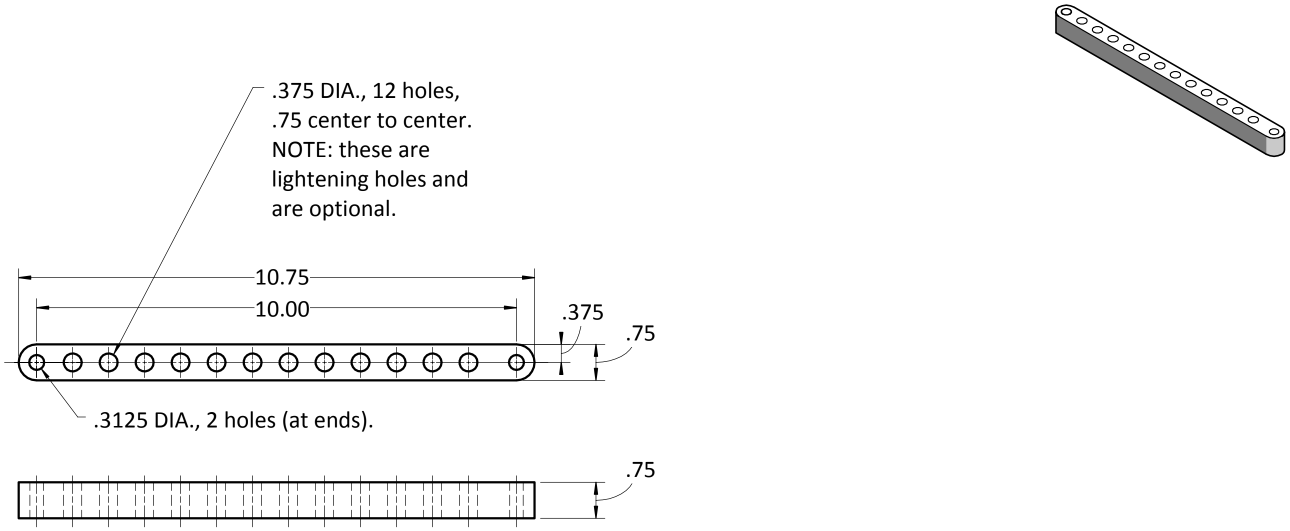


.375 DIA., 25 holes,
.75 center to center.
NOTE: these are
lightening holes and
are optional.

.3125 DIA., 2 holes (at ends).

Radius both ends.

PART # 39



.375 DIA., 12 holes,
.75 center to center.
NOTE: these are
lightening holes and
are optional.

.3125 DIA., 2 holes (at ends).

PART # 40

▨

material:
6061-T6 alum.

stock size:
.75 x .75

required: 1 ea.

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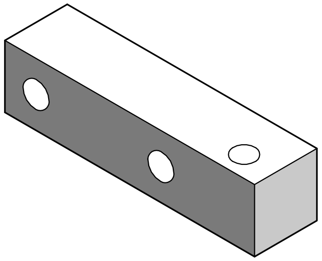
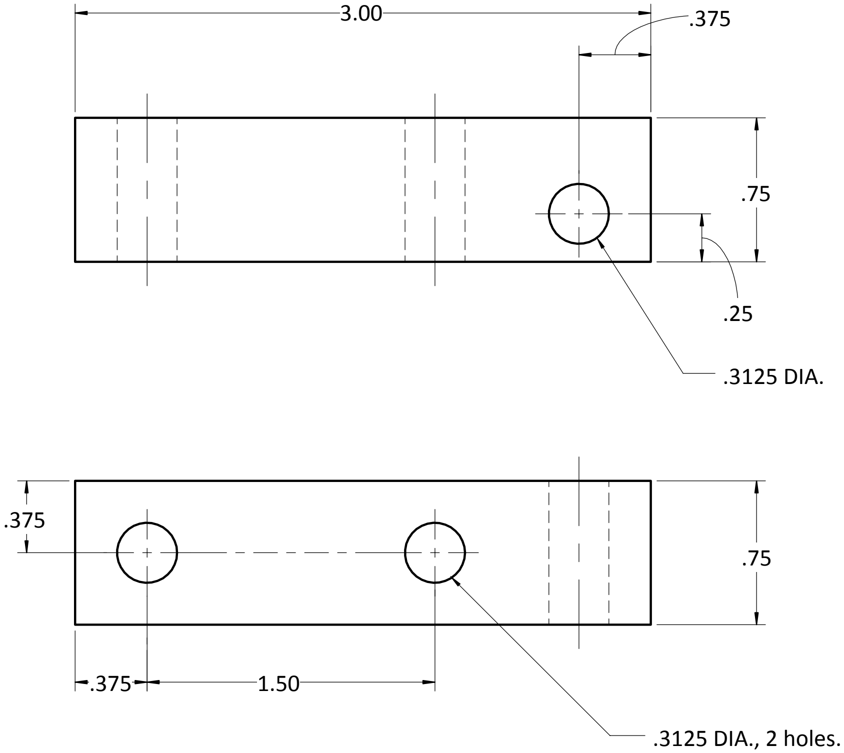
part #s 39,40





▨

material:
6061-T6 alum.

stock size:
.75 x .75

# required: 1

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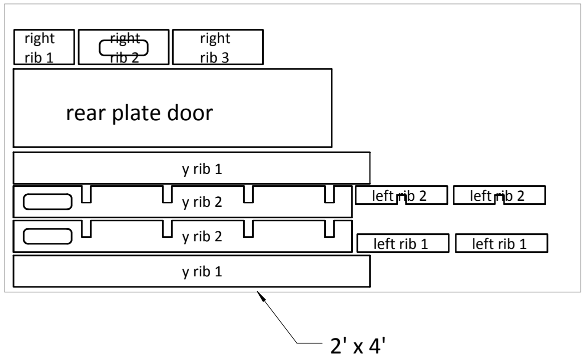
part # 41

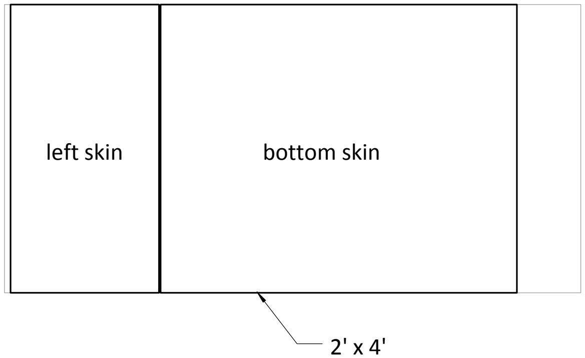
PLYWOOD LAYOUT NOTES:

These are suggested layout of parts on plywood sheets when using 2' x 4' pieces.

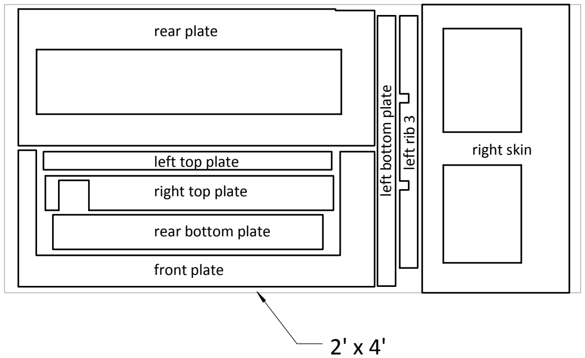
Leave space for width of saw cuts.



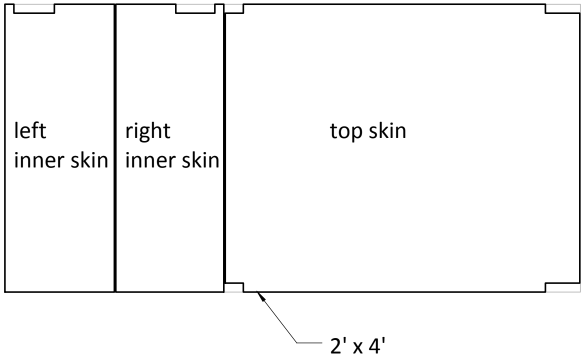
2' x 4'
3/4" birch finish plywood.



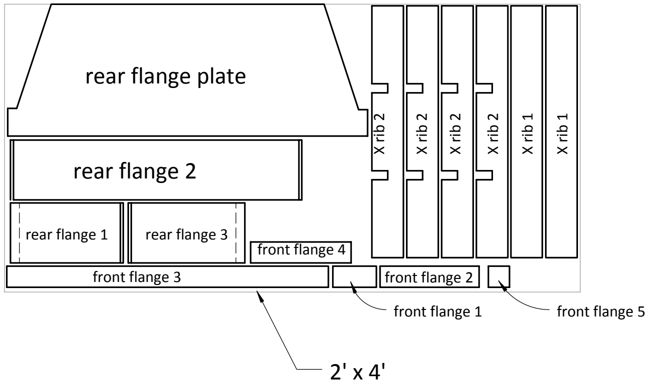
2' x 4'
1/4" birch finish plywood.



2' x 4'
3/4" birch finish plywood.

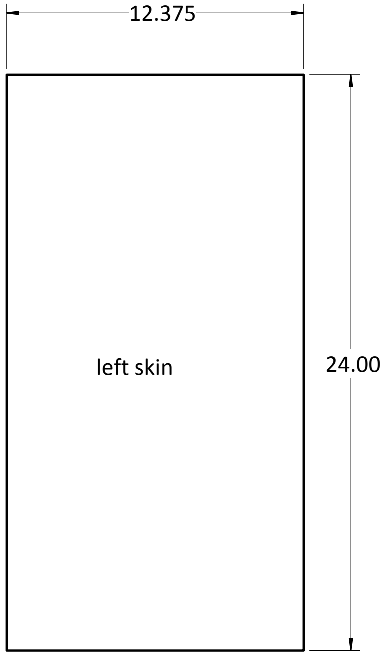


2' x 4'
3/8" birch finish plywood.



2' x 4'
3/4" birch finish plywood.

(1X)



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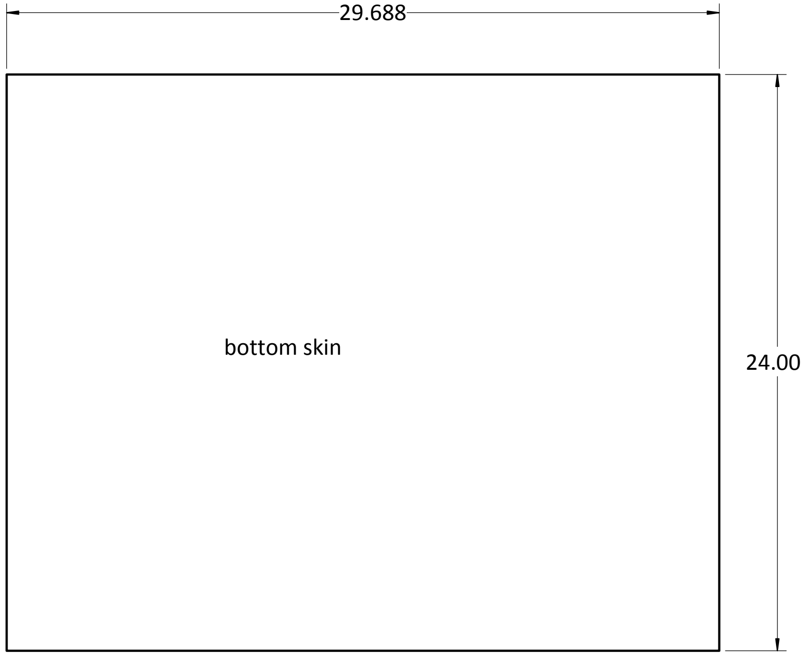

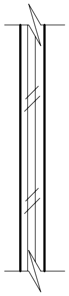

material:
finish quality
birch plywood

stock size:
1/4" thickness

# required:
as indicated

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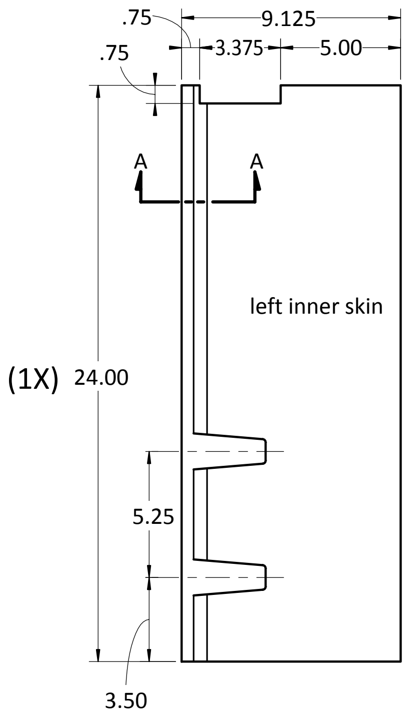
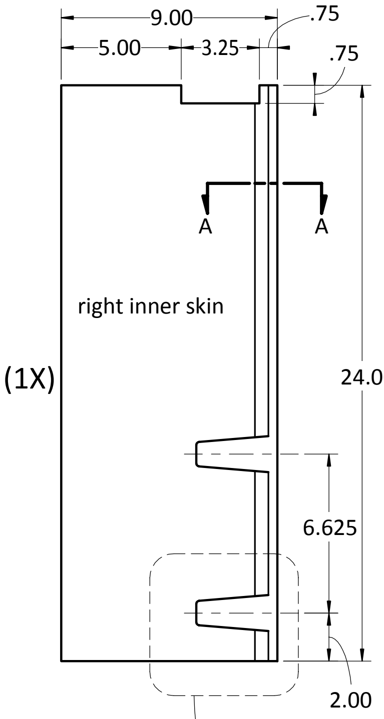
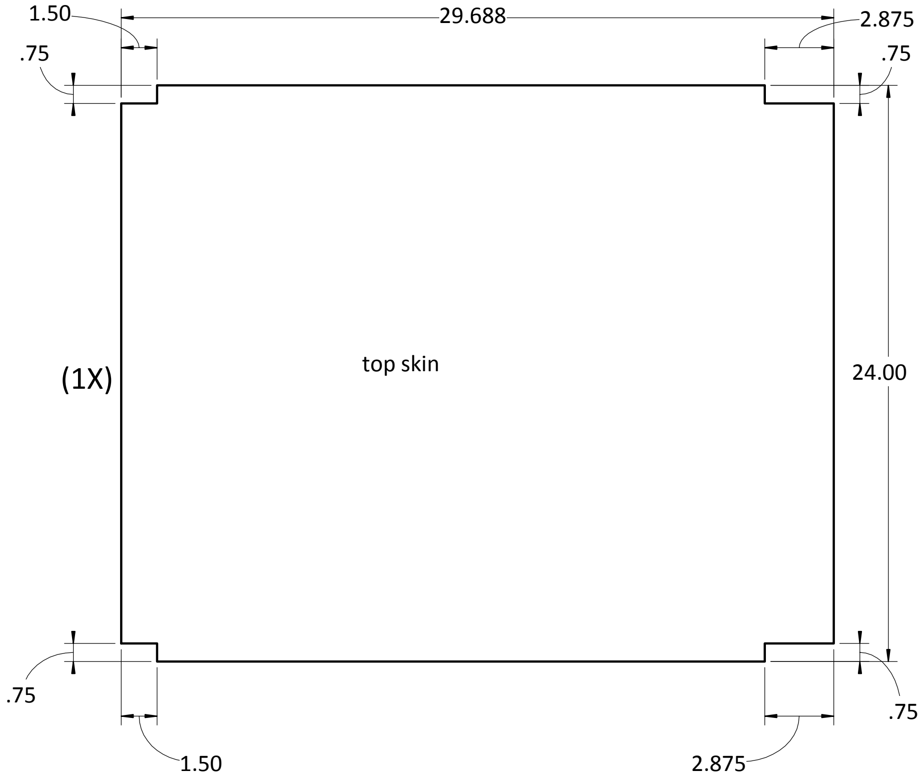
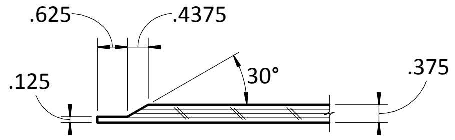
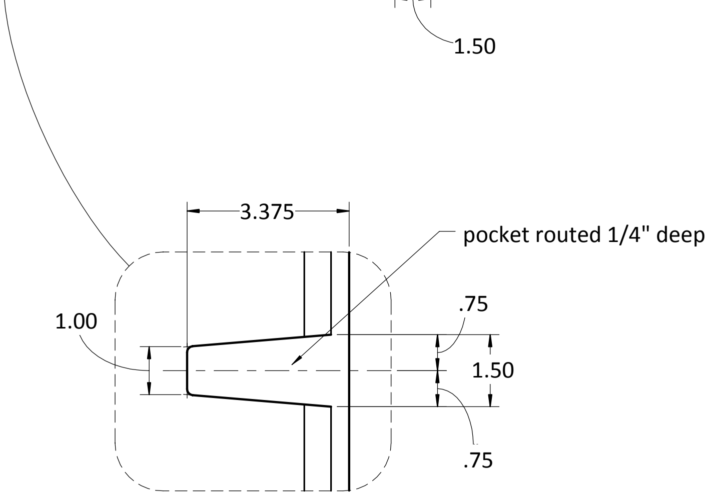








Section A-A



Typical pocket, enlarged detail.

material:
finish quality
birch plywood

stock size:
3/8" thickness

# required:
as indicated

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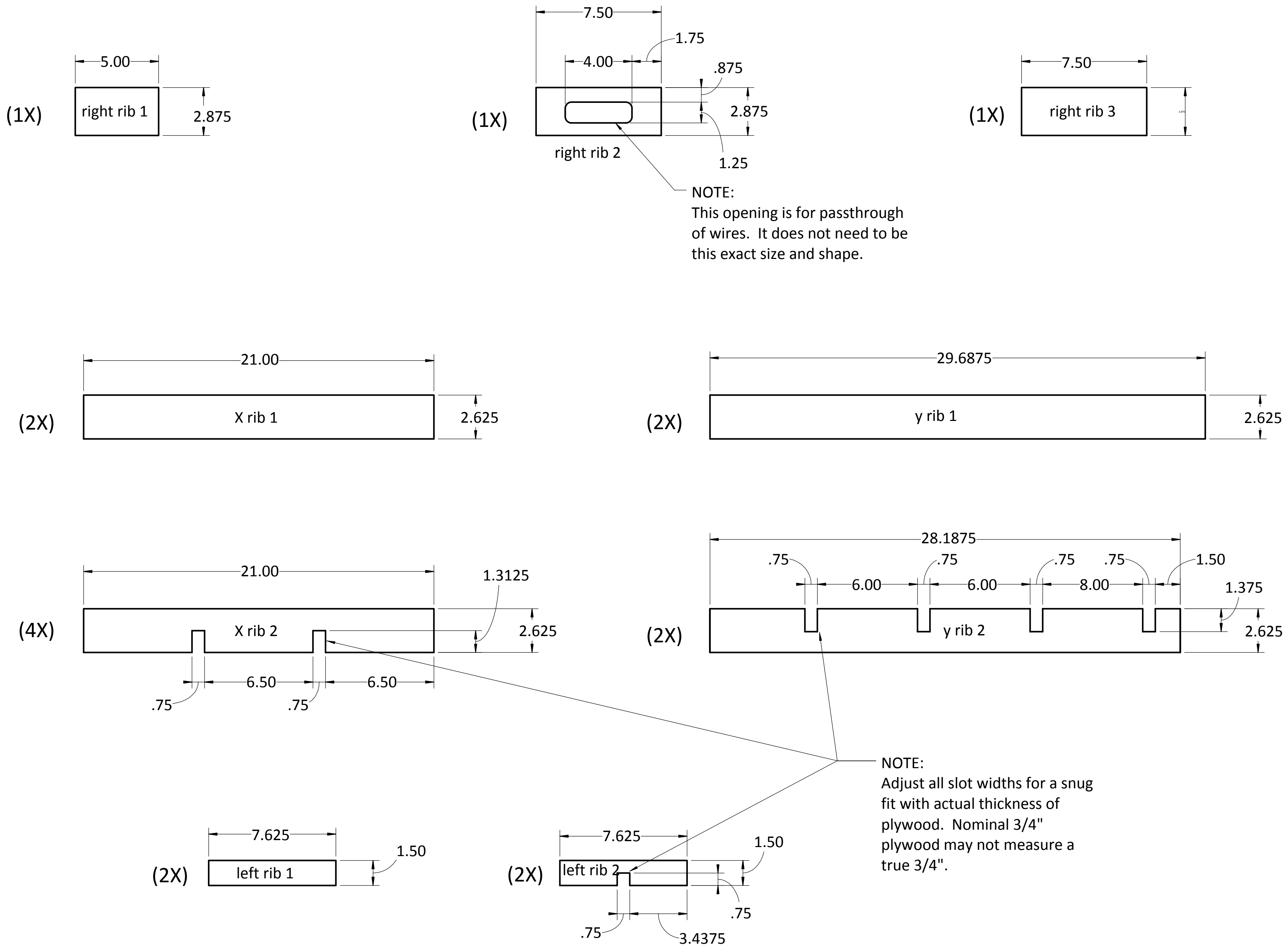
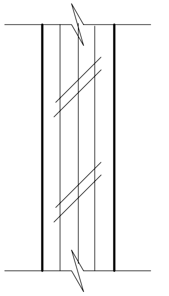


NOTE:
This opening is for passthrough of wires. It does not need to be this exact size and shape.

NOTE:
Adjust all slot widths for a snug fit with actual thickness of plywood. Nominal 3/4" plywood may not measure a true 3/4".



material:
finish quality
birch plywood

stock size:
3/4" thickness

# required:
as indicated

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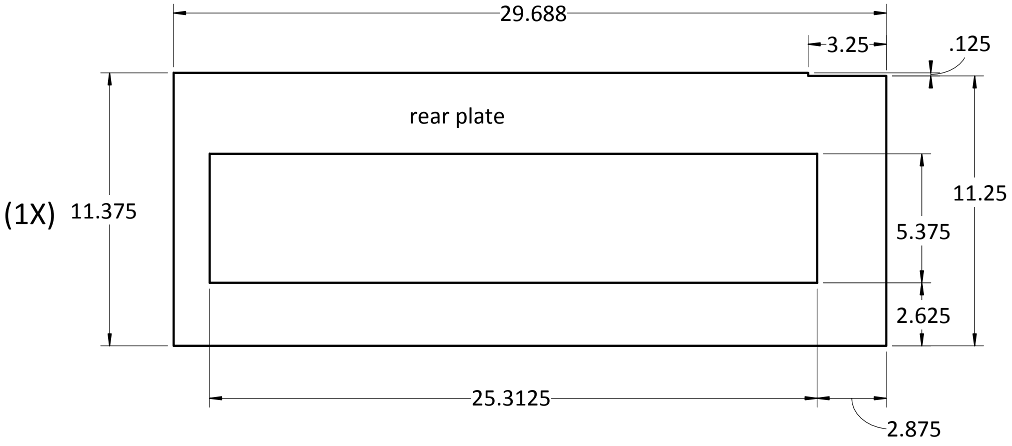
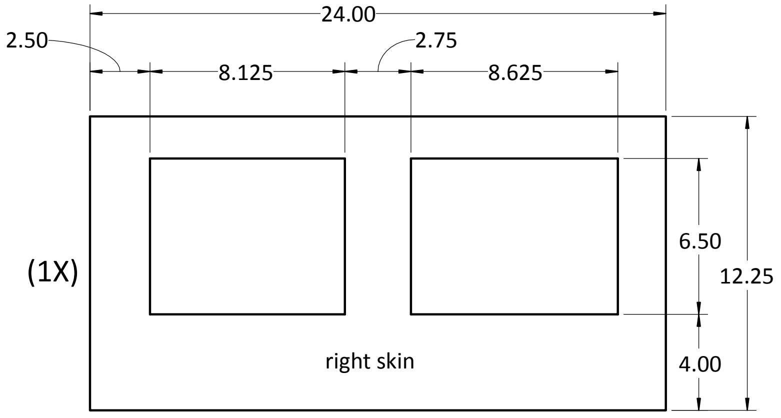
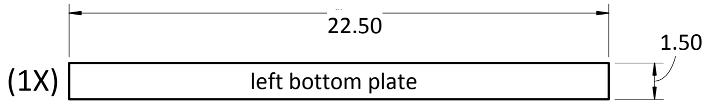
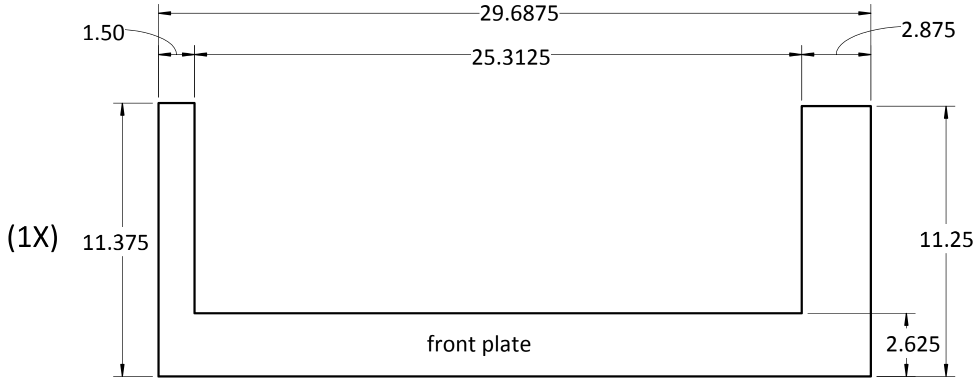
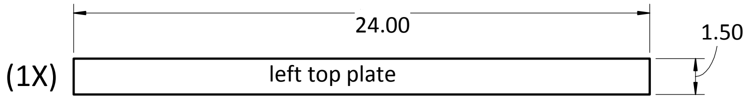


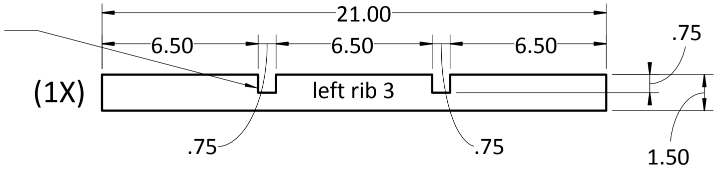


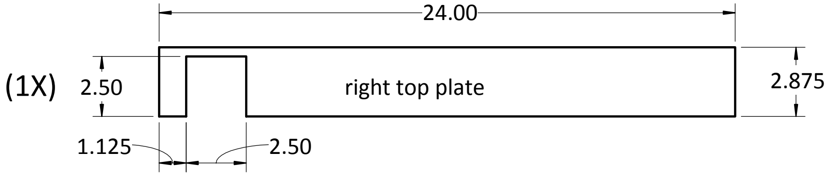


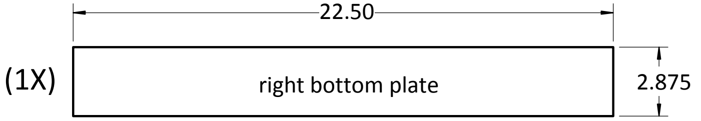


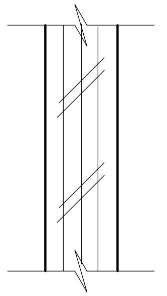


NOTE:
Adjust all slot widths for a snug fit with actual thickness of plywood. Nominal 3/4" plywood may not measure a true 3/4".









material:
finish quality
birch plywood

stock size:
3/4" thickness

# required:
as indicated

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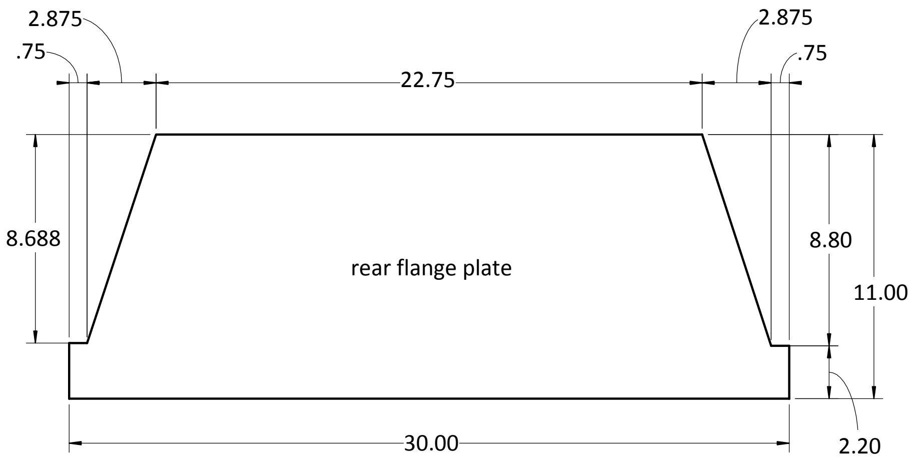
(1X)



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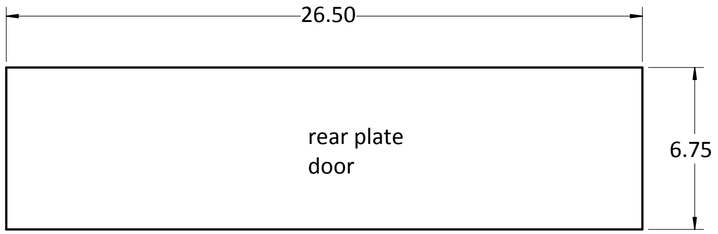

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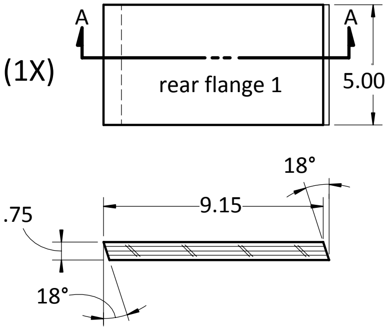
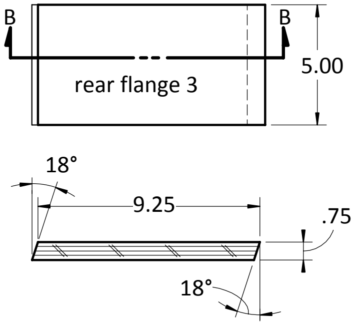


Section A-A

(1X)



Section B-B

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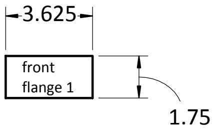

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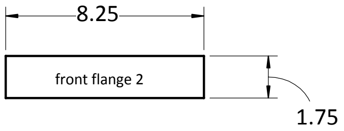
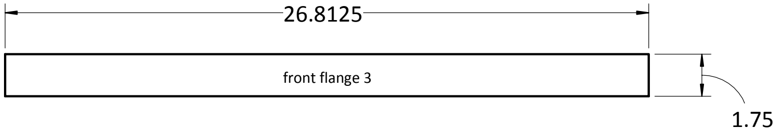


(1X)



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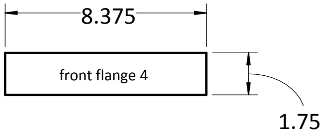

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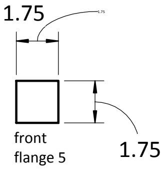

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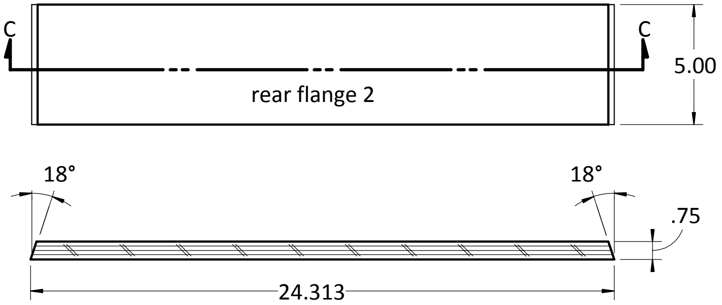
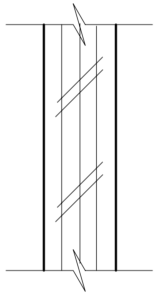


Section B-B



material:
finish quality
birch plywood

stock size:
3/4" thickness

# required:
as indicated

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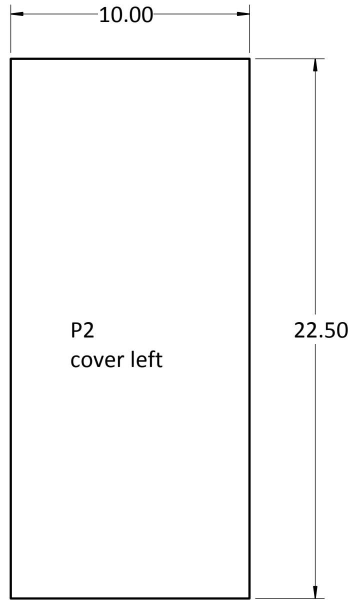

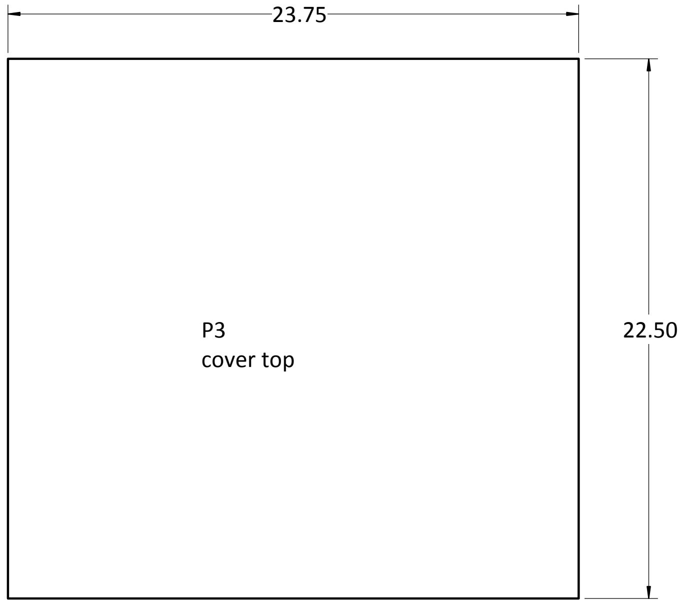

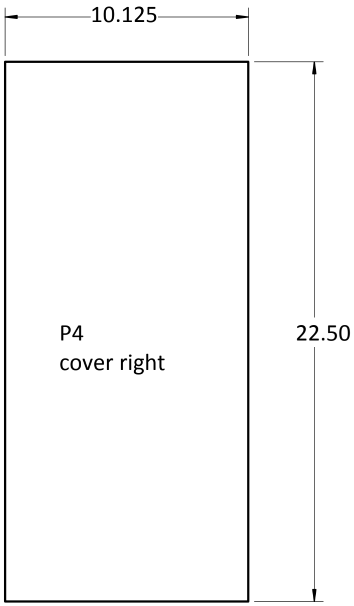

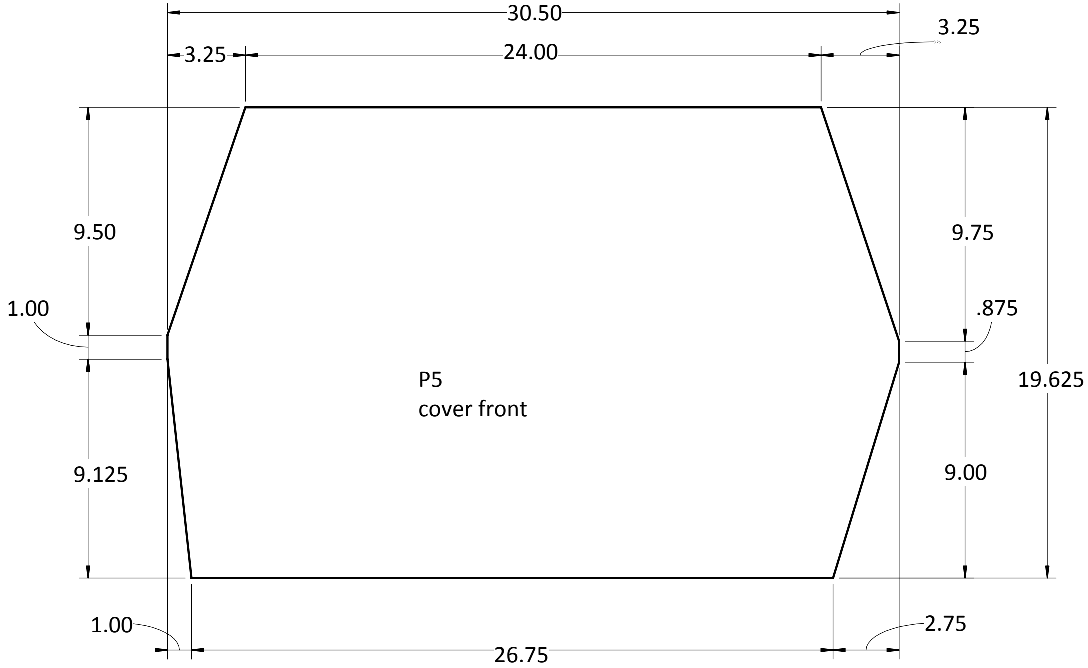

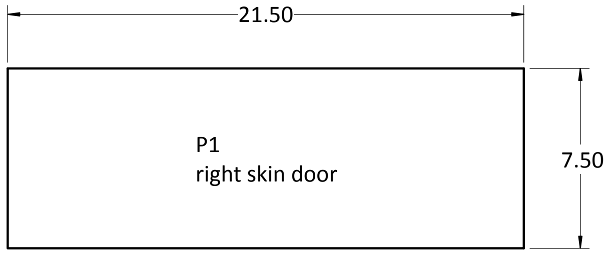

material:
polycarbonate
sheet

stock size:
.125 min.
thickness

# required: 1 ea.

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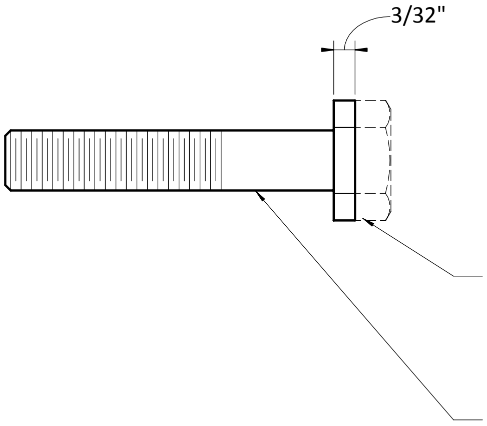
BENCHTOP CNC ROUTER PLANS

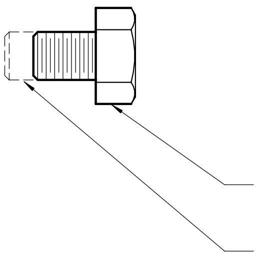
version 1.2



file/grind head of bolt to leave approximately 3/32" thickness remaining.

5/16 x 1 1/2" bolt

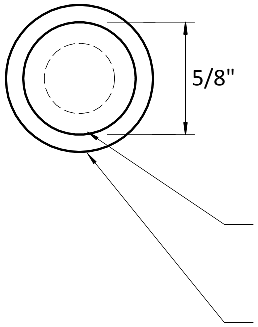
(8) modified bolts required



1/4-20 x 1/2" bolt

shorten bolt to approx. 3/8" thread length. These attach the X rails to the rail angles, and may need to be tested and adjusted for exact length required.

(14) modified bolts required



file inside diameter to approximately 5/8"

washer to fit 5/16 bolt.

Note that outer diameter of washers vary between manufacturers. Make sure outer diameter is larger than the outside diameter of the 22mm bearings. If it is not, use a washer with a larger outside diamter.

washer W1
(6) modified washers required

WOOD FABRICATION

All of the wood parts can be fabricated with relatively simple woodworking equipment. I did nearly all of the cutting with a cordless Makita circular saw (right photo). This saw is very light and manueverable and, when used with a fence that is clamped to the material, is capable of just about all cutting needs in this project.

I did use a table saw for a handful of cuts (primarily the inner ribs) to make it easier to keep their dimensions consistent, but those could also be cut with a circular saw and fence.

The few cuts that can't easily be done with a circular saw or table saw can easily be done with a router. This project is designed to use a laminate trimmer, such as the one to the right, as the spindle, so now is the time to buy one if you don't already own one. I specifically designed the mounts on this machine for a Ridgid model R2400. Any laminate trimmer of similar size should be able to be adapted to the design, but may require some slight modifications to the machine mounts.

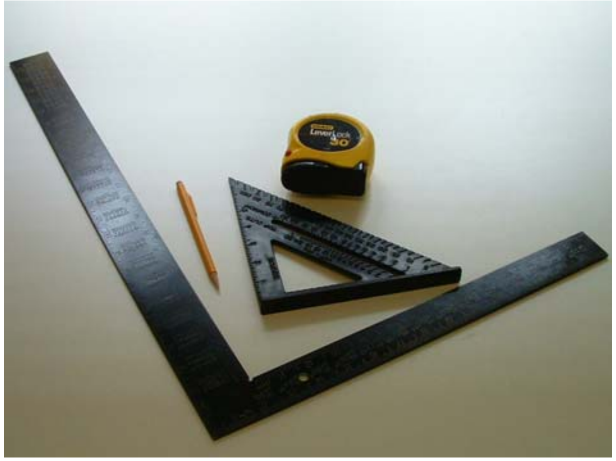
I used the router to cut several of the wood pieces in the project. The inner skin pieces have a complex rabbet along one edge, as well as a series of surface pockets. The router easily handles these situations.

I use spiral up-cut bits rather than the inexpensive straight type bits. These are similar to an end mill used in a milling machine, but have flute angles and cutting angles that are specifically suited for wood. The increase in cutting performance over bits with a straight cutting edge is well worth any additional cost.

What makes both the circular saw and the router so versatile is to use them with a fence. I use a piece of 1" x 2"rectangular aluminum tubing and a couple of C-clamps to hold it in place. With careful setup you can make very accurate cuts.

Don't forget both hearing and eye protection. These are _not_ optional!

A few simple layout tools are required. A good quality framing square, a triangle, tape measure, and a pencil. Make sure the square and triangle are actually at 90 degrees. It may seem obvious that they would be, but low quality versions can be very inaccurate. You can check accuracy by placing it along a known straight edge and striking a perpendicular mark. Flip the square or triangle 180 degrees and make another mark parallel to the first. If it is in square, the lines will be exactly parallel. If not, the lines will becloser together at one end or the other. Note that this test is only as accurate as the straightedge you are using.

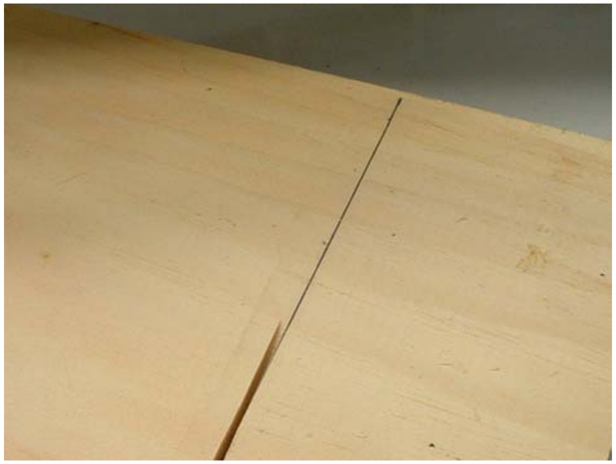


When drilling holes in wood, a set of brad-point drill bits is worth the investment. They cut a considerably cleaner hole than regular twist bits that are designed for metal.

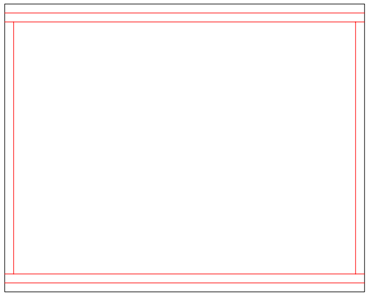
In addition to the tools shown, you will most likely need a few other traditional hand tools. I found need for a hand-saw, chisels, hammer, a nail set, etc.. I also used a random orbital sander prior to painting the base.

Whatever selection of tools you end up using, what is important is accuracy in layout and cutting. Be careful to make precise measurements and thin, crisp pencil marks. Cut to the waste side of the line as seen in the photo to the right to keep the desired dimensions of the finished pieces.

Okay, time to refer to the drawing sheets for the wood parts and start cutting! Cut all of the wood parts on pages 73-78.



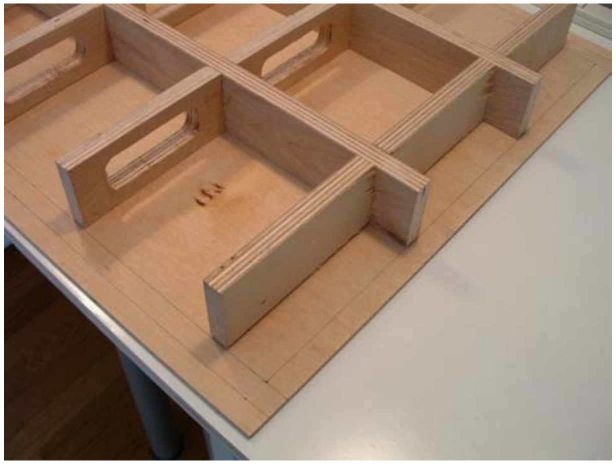
version 1.2

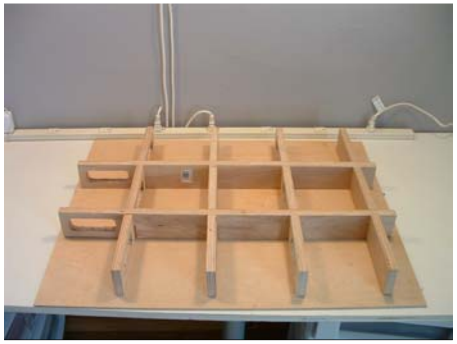


ASSEMBLY OF WOOD COMPONENTS

On the bottom skin (part A), draw the pattern of lines that are shown in red in the diagram to the left. The lines are all spaced 3/4" apart.

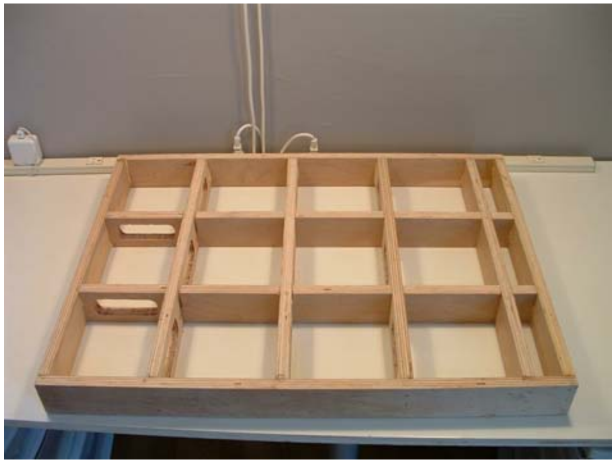
Slide the X and Y ribs together as shown in the middle left photo. Place them onto the bottom skin as shown in the top right photo. The ends of the ribs should all fall along the drawn lines as shown. If everything looks like it fits correctly, take the ribs back apart, apply carpenters glue to the joints, and reassemble.





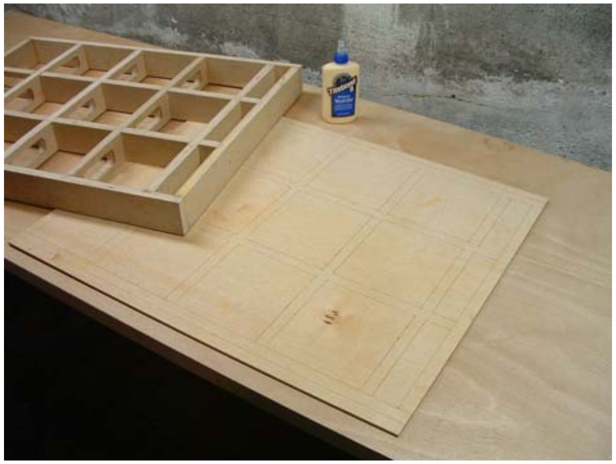
Apply glue to the ends of the ribs and attach the perimeter ribs as shown in the photo to the right. Nail them together with 4d finish nails, or with a pneumatic nail gun.

Place the rib assembly back on the bottom skin and make sure it aligns with the pencil marks. With a pencil, mark around each rib onto the bottom skin.

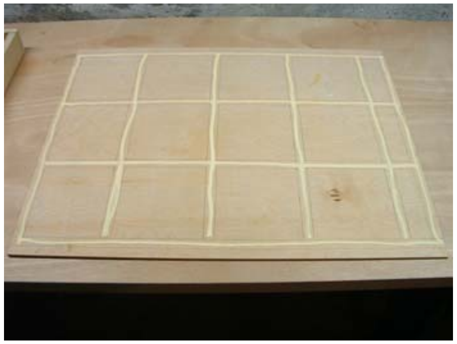


NOTE:
The parts depicted in these photos have oblong holes cut into the ribs. This was for an untested experiment to use the base as a vacuum table. They are not needed unless you would like to attempt experimenting with this idea on your own. The part drawings do not show their sizes or locations.

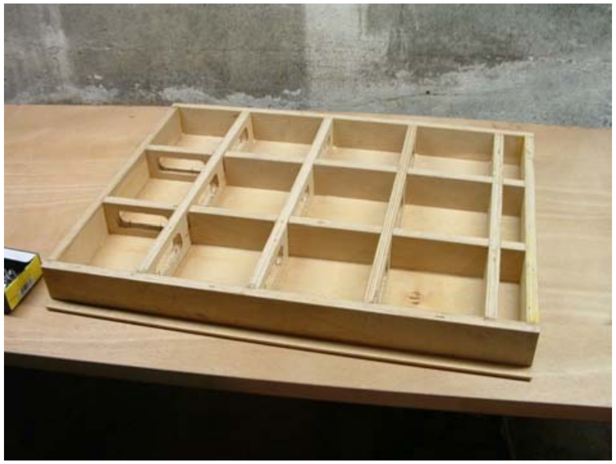
Move the rib assembly to the side and apply carpenter's glue where the ribs contact the bottom skin. Use the pencil marks as a guide.



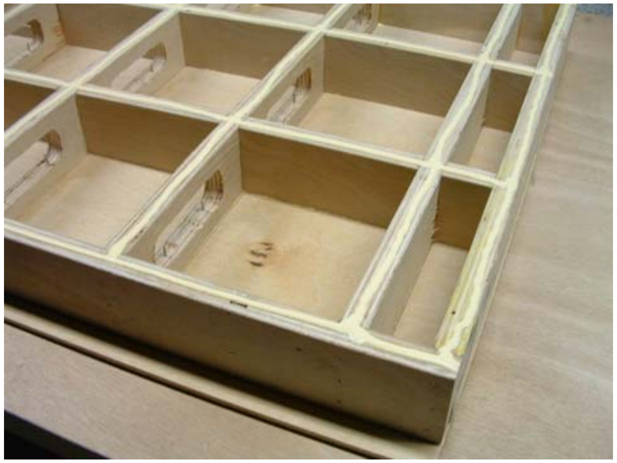
version 1.2



With glue applied, reposition the rib assembly on the bottom skin. Carefully flip it over. Make sure the ribs are still in correct alignment, and attach the bottom skin with 4d finish nails or with a nail gun. Mark the centerlines of the ribs onto the skin with a pencil to accurately position the nails into the ribs. It is important while doing this step to be working on as flat a surface as possible. If the work surface is not exactly flat, any warpage will be transferred to the assembly.

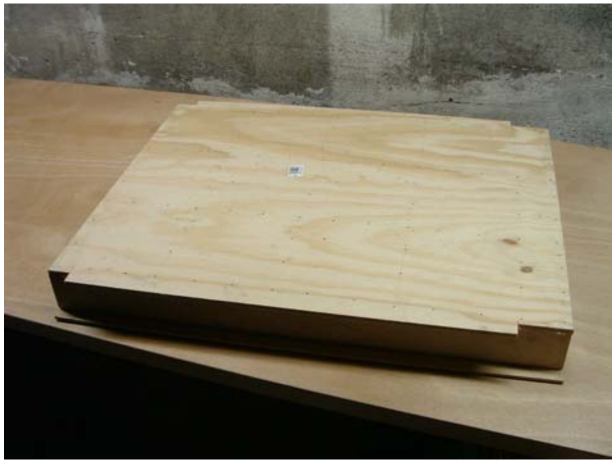


Flip the assembly so it is right side up again. Apply glue to the top edges of the ribs as shown in the photo to the right.

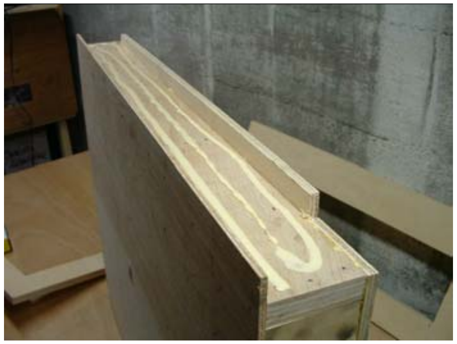


Place the top skin onto the ribs, and make sure it is accurately positioned. The "tabs" along the longer edges will protrude 3/4" out beyond the ribs. All other edges should align exactly with the outside surfaces of the ribs.

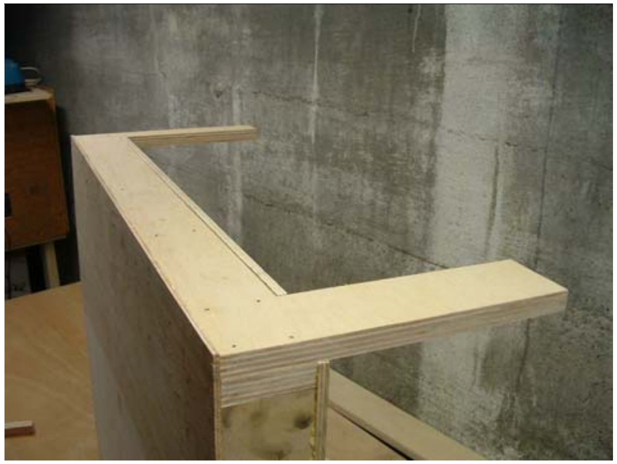
If it is aligned correctly, fasten it in place as well. As soon as this skin is attached, the assembly will become very rigid. This means that it is very important to keep the assembly flat to the work surface. Check often that it is still lying flat. Once the top skin is fully attached, the assembly cannot be pushed back to being flat if it has any warp or twist.



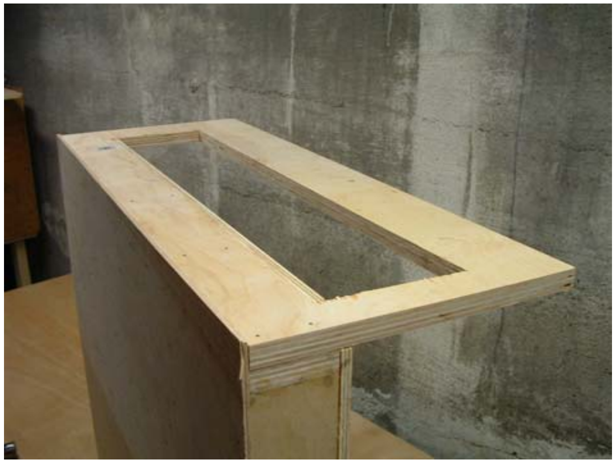
version 1.2



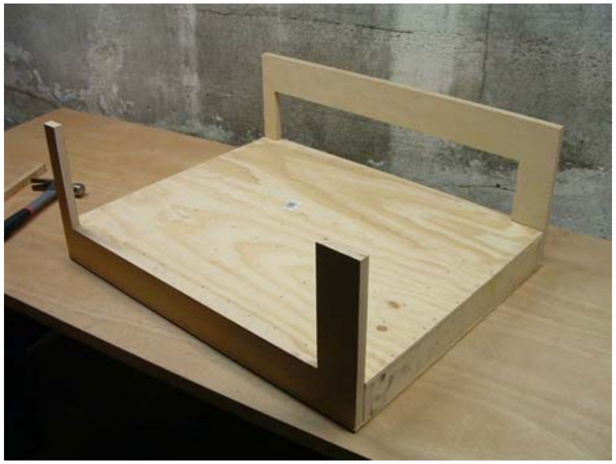
Apply glue to the front Y rib as shown in the photo to the right, and spread it so that it evenly coats the surface. Place the front plate into position as shown in the photo to the right. Fasten it in place with 4d nails.



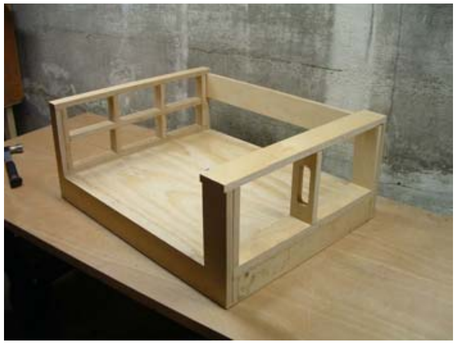
Do the same with the rear plate as shown in the photo to the right.



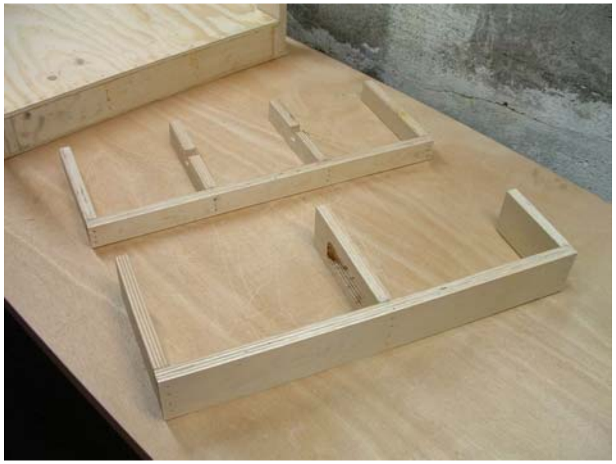
You should now have an assembly that looks like the photo to the right.

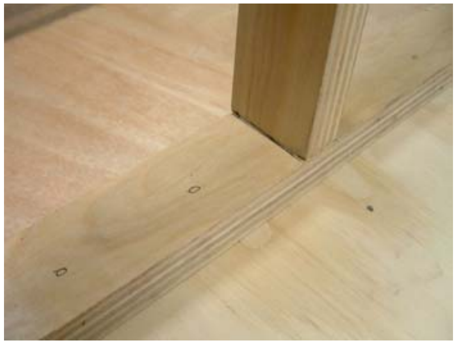


version 1.2

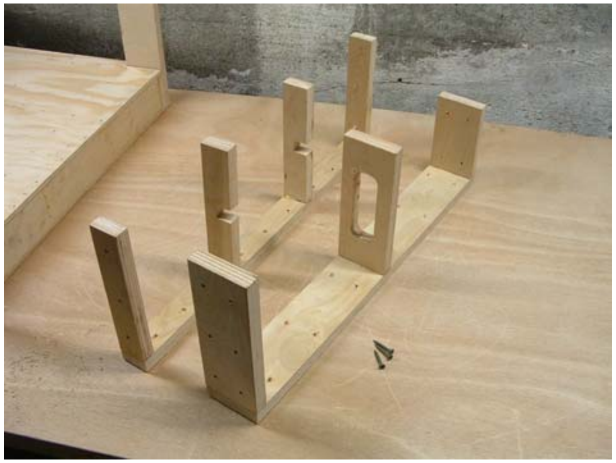


Trial fit all of the left and right ribs, and their corresponding top and bottom plates, as shown in the photo to the left. If all fits well, disassemble them. Glue and nail the ribs that are oriented vertically to their bottom plates as shown in the right photo.

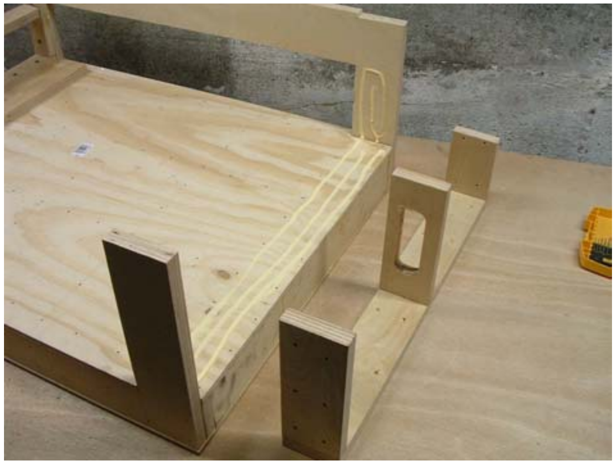


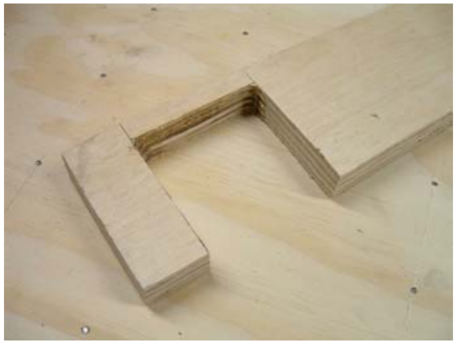


Mark the bottom plates, and the end ribs as shown in the photos to the left and right, for drilling of holes. Screws will go through these holes to attach the assemblies to the base, so use a drill bit that is slightly larger in diameter than the screws. Use either #8 x 1 1/4" wood screws, or high quality decking screws of a similar size.



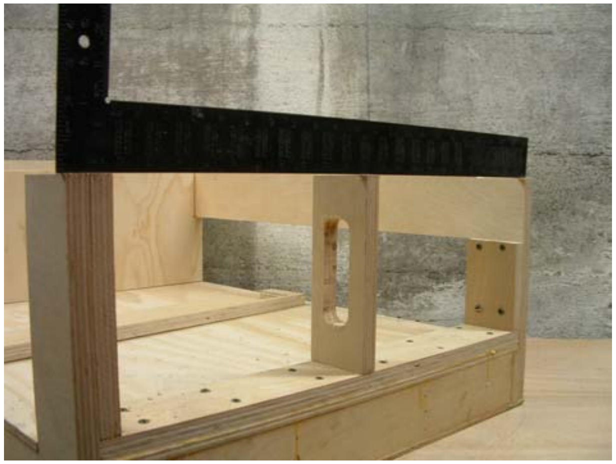
Apply glue to the surfaces where these assemblies will join. Spread it evenly and position the rib assemblies. Screw them into place, being careful that they do not shift out of position as the screws tighten.



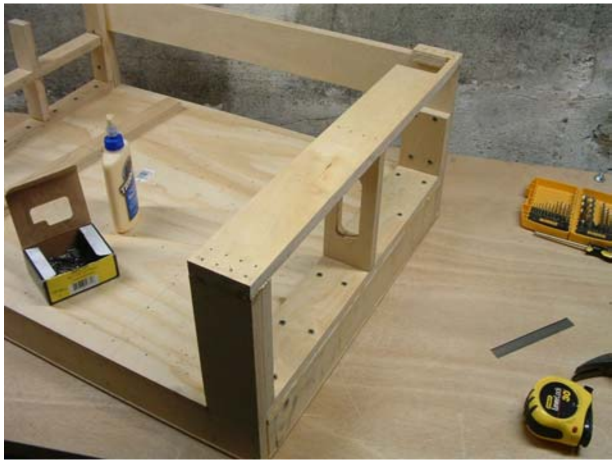


The notch in the right top plate was cut out using the router. This notch will provide clearance for the stepper motor.

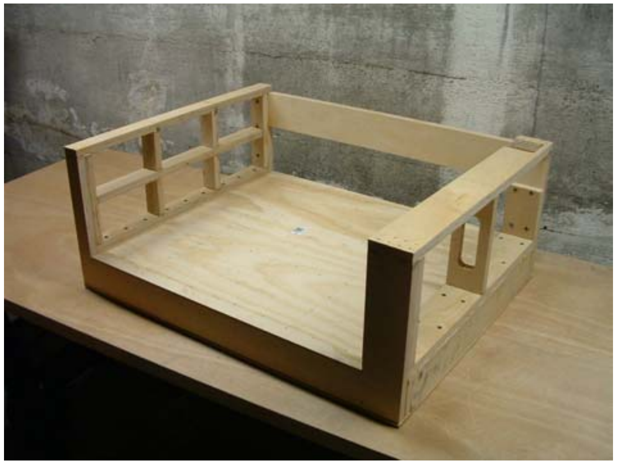
Place a straightedge across the tops of the ribs as shown in the photo to the right. If they are not all exactly the same height then either trim the ones that are taller or shim the shorter ones as necessary so that their tops are parallel to the base. Measure up to the straightedge at several points to check this. Shims can be made of paper or thin paperboard if necessary. The tops of the ribs need to be exactly the same height so that the top plate will be flat when installed.



When satisfied that the tops of the ribs are aligned, apply glue to them and attach the top plate with nails, as shown in the photo to the right.

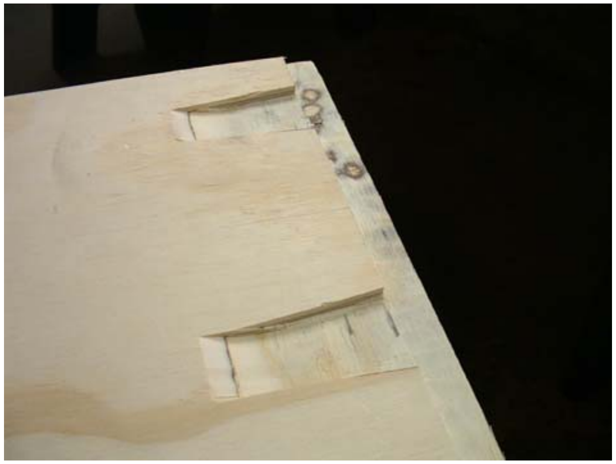


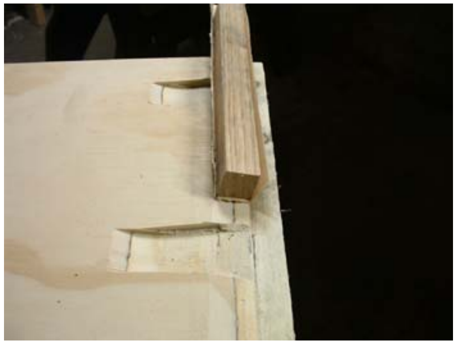
Use the same procedure to align the top surfaces of the left ribs, and install the left top plate. Also apply glue to the joint areas and install the center horizontal rib. The assembly should now look llike the photo to the right.



version 1.2

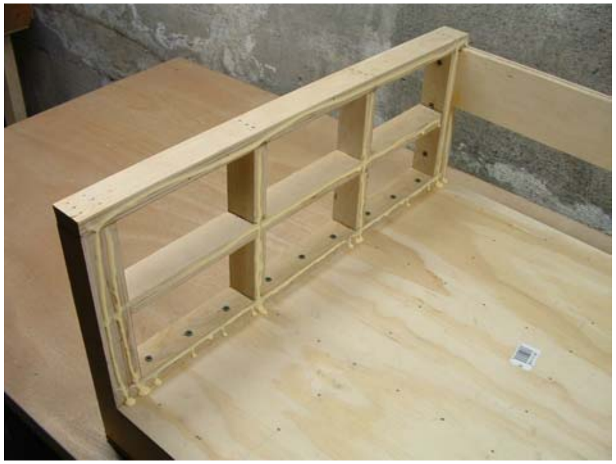
The inner skins (parts U and V) have a complex rabbet cut along their top edges, and have pockets cut into their surfaces. The pockets are to provide wrench clearance to be able to adjust some of the bearings on the machine. All of these cuts can be made with the router. I made small incremental cuts,using a clamped guide fence for accuracy. Relocate the fence for each incremental cut. Start at the outer edge of the part, and work progressively farther from the edge. When you get to the beveled zone, make shallower and shallower cuts to create the bevel. A ball-end bit will give a cleaner surface finish to the beveled area.



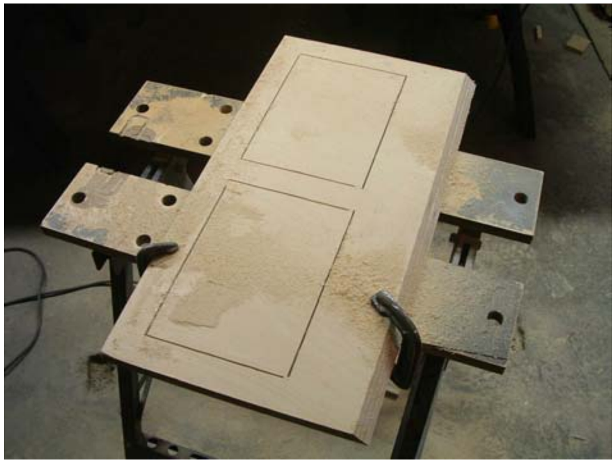


Making incremental cuts works well to cut the shallow bevel angle, however, it leaves a slightly stepped surface finish even when using a ball-end bit. This can be smoothed out with sandpaper and a sanding block.

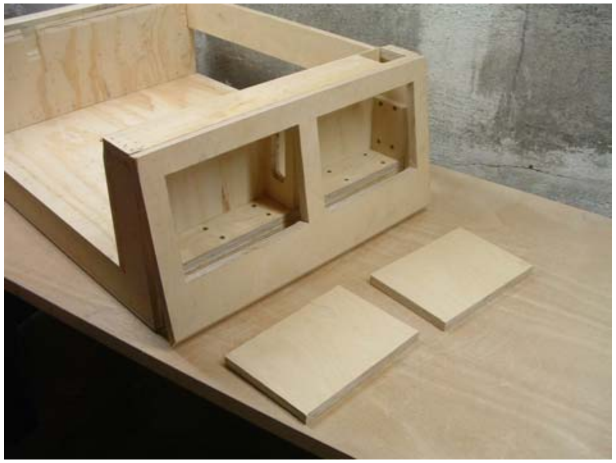
Apply glue to the ribs where the inner skins will be attached, and fasten the skins in place with 4d finish nails.



The right skin (part W) has two openings cut into it for access to the area where the electronics will be housed. These can be cut in several ways. I used a circular saw for a series of careful plunge cuts. The cuts were then completed at the corners with a hand saw. However, I would suggest using the router to cut these openings. A plunge cut with the circular saw can be dangerous. Any rearward movement while plunging into the work and the saw can kick backwards toward your body.



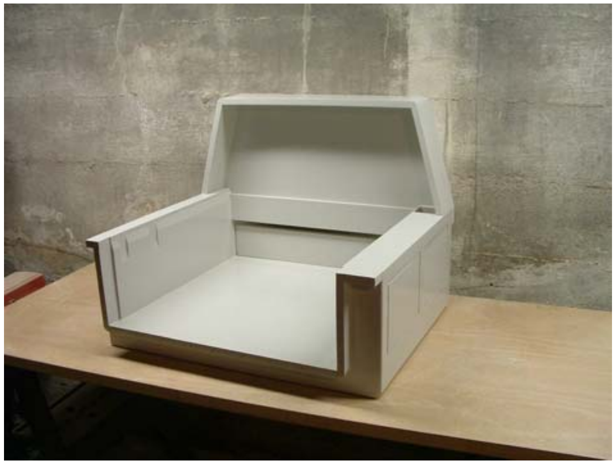
Attach the left and right skins. Note that the cutouts are waste, and are not used.



Using the exploded view drawing on page 35 as a guide, assemble the rear cover flanges and flange plate (parts FF, GG, HH, II). Note that this assembly is just resting on the machine base in the photo to the right. It will be attached in a later step. The rear door is also shown just resting in position. It will also be installed in a later step.

Also attach the front flanges. The front flanges can be attached by drilling clearance holes and using long (approx 2 1/2") #8 wood screws, or decking screws of similar size.

Use a nail set to sink the heads of all nails slightly below the finish surfaces. Use wood putty to fill the nail heads and sand smooth when it is dry. The machine base can now be primed and painted.



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FABRICATING THE METAL PARTS:

The most efficient method of fabricating the parts is to do each type of operation all at once. More in depth descriptions of each step are on the following pages. I used the following fabrication sequence:

1. Cut all of the pieces to their overall lengths.
While holding the parts in a vice, file the cut ends to clean them up, making them as perpendicular as possible to the part.

2. Lay out all locations of holes and any secondary cuts with a marker and scribe. A few of the parts, such as the Z axis nut plate, have angled cuts. Drill the holes before making these cuts, as it will be easier to hold the piece while drilling if it is still rectilinear in shape.

3. Center punch all of the holes.
Use a spring loaded centerpunch for accuracy and speed.

4. Drill all holes.
I found it quickest to drill all of each size hole at once. So I kept the same size drill bit chucked in the drill press and drilled all of that size in all of the parts before changing bits to another size. I found it to be faster to clamp and unclamp parts in the drill press vice than to constantly change drill bit size while working on only one part at a time.

5. Drill counterbores.
Here I found it easiest to drill the primary hole, keep the part clamped, change the bit, and then drill the counterbore.

6. Tap all threaded holes.

7. "Cut" the large and complex part shapes, such as the router mounts, by drilling a series of closely spaced holes to nibble through the material. Use a hand file to finish the parts.

8. Fabricate the studs.
Referencing the stud schedule, cut all of the steel studs to length from threaded rod. File the ends flat, with a chamfer around the edge. Some people thread a nut onto the rod before cutting, so that when the nut is removed it straightens any thread deformation. I found this to be unnecessary if finish filing was done properly.
Keep the finished studs organized. I taped all of each length together with masking tape and labeled them to keep things organized.

9. Fabricate the modified hardware.
Referencing the drawings, modify the bolts and washers as indicated. These modifications are all done with a file. Keep these finished parts organized as well.

Metal Fabrication Sequence

1. Cut Lengths

2. Hole Layout

3. Centerpunch Holes

4. Drill Holes

5. Counterbore

6. Tap Holes

7. Plate Cuts

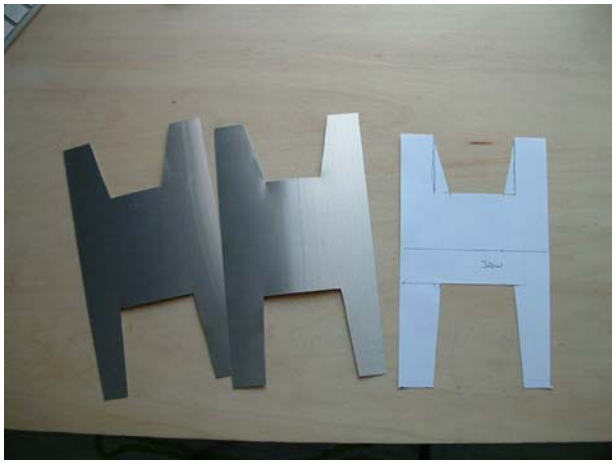
8. Studs

9. Hardware

METAL FABRICATION

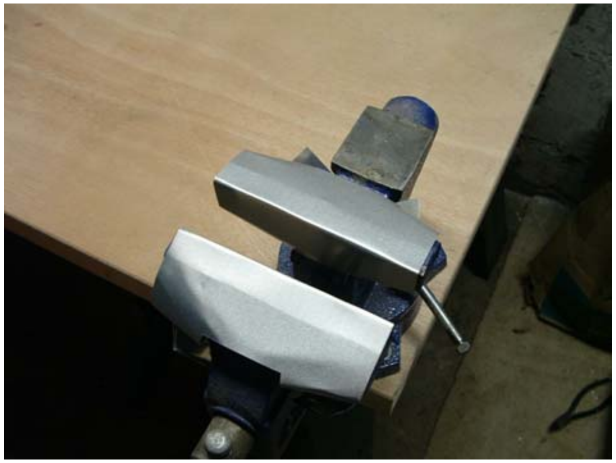
Most vices have jaw faces that are serrated. Using these to clamp aluminum parts can badly mar the finish surface. The solution is to buy or fabricate a set of jaw covers. There are commercial versions available in many types of non-mar materials: brass, plastic, rubber, etc. I quickly made a set to fit my vice out of a piece of common aluminum roofing flashing.

Taking some measurements, I transferred this information to a paper pattern. The idea is that the covers wrap part way around the jaws to hold themselves in place. It took a couple of adjustments to arrive at a pattern that seemed like it would fit well. I used a sheet of card stock/ cover stock so it would be durable as a pattern.

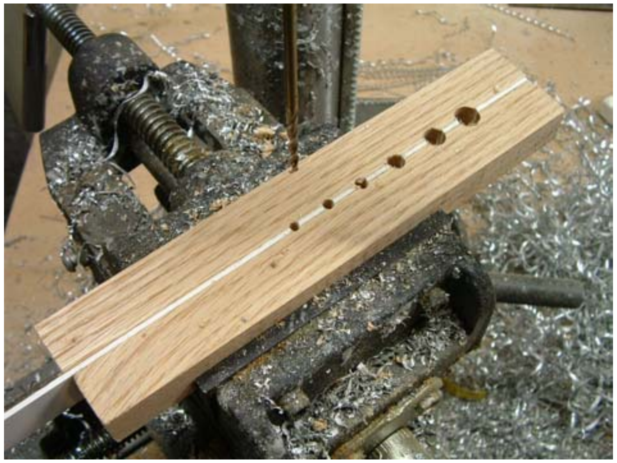


I transferred the pattern to the aluminum sheet with a fine tipped marker. The aluminum can be cut by scoring with a utility knife blade and then lightly bending it back and forth. It will snap off cleanly along the score mark. The material is thin enough that curves and inside corners can be cut this way.

Wrap the cover as tightly as possible around the vice jaws. It is ok if they are slightly floppy. This aluminum is very thin, and will wear out after some use, so keep the pattern to make more covers in the future.



Another helpful clamping device is a block to hold round stock in the vice, such as threaded rod. I quickly fabricated a set out of two lengths of 3/4" square oak stock. I clamped them together with a strip of paper mat-board between them as a spacer (cardboard or a thin strip of wood would work fine). Drill a series of holes in common sizes. These are very helpful when making studs from threaded rod. They work wonderfully to hold them without damaging the threads while filing their ends flat (as in the photo to the left).

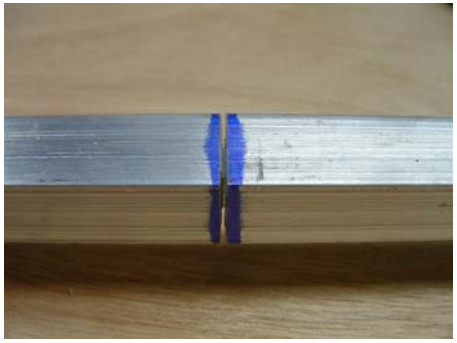


To mark the locations of cuts on the lengths of material, I used the tools to the left. A steel engineers scale with 1/64" divisions, a felt tip marker, a carpenters awl, and a small square. To measure pieces longer than the short scale I used a 24" carpenters square, hooked over the end of the material. See page 94 for a photo of this. I found that a blue marker worked better than a black one. It seems to have better contrast when a line is scribed through it. Blue is also the color of the traditional machinist's dye that is used for this operation.

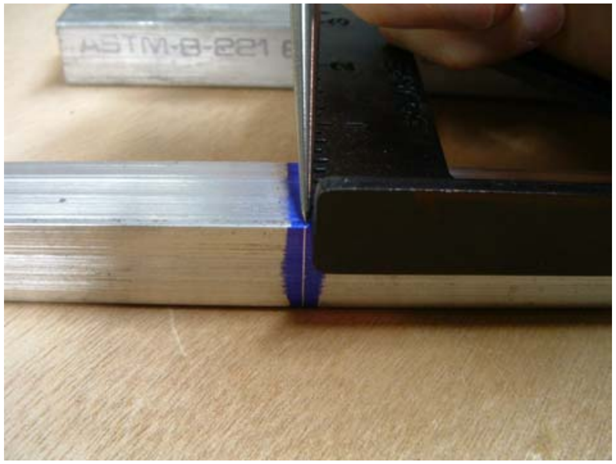
Mark the area where the cut is to be located with the felt tip marker. The scratch awl is used for just that- to scratch a thin, accurate line through the area of color. The scribed line should not go deep into the material, just enough to go through the marker. If you wash the marker off you should just barely be able to see the scribe line, and barely be able to feel it with a fingernail.

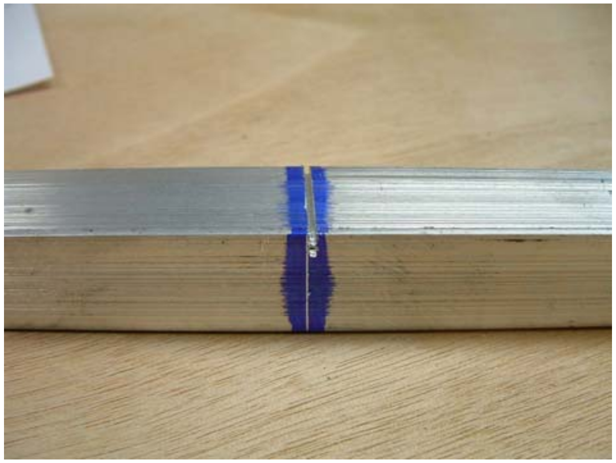
Use the square to continue the scribe line all the way around the material. The end of the last line should meet up exactly with the first line. This will serve as a check that you are marking precisely perpendicularly to the edge.

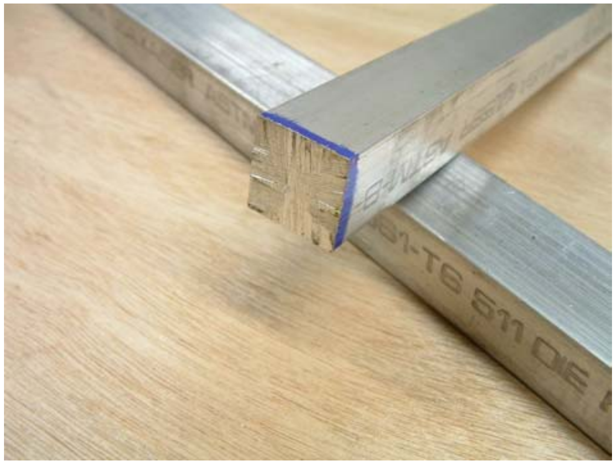
With the piece clamped in the vice, begin cutting with the hacksaw. Note that the cut is just to the side of the scribed line. It just barely leaves the scribed line on the finished piece. Use the edge of your finger as a guide for the blade and begin to cut carefully and slowly. Keep the blade horizontal and only apply pressure on the forward stroke. After cutting about 1/8"-3/16" deep remove the piece, rotate it 90 degrees and make another cut on this face, also about 1/8" - 3/16" deep. Continue this all the way around the perimeter of the part (illustration to left).



Like the scribing, the last cut should exactly line up with where you began. With a consistent 1/8" -3/16" groove all the way around the part, make a final cut all the way through. The groove will help guide the blade straight through the material on the final cut. The completed cut should now be perpendicular to length of the material and require minimum clean-up with a file.

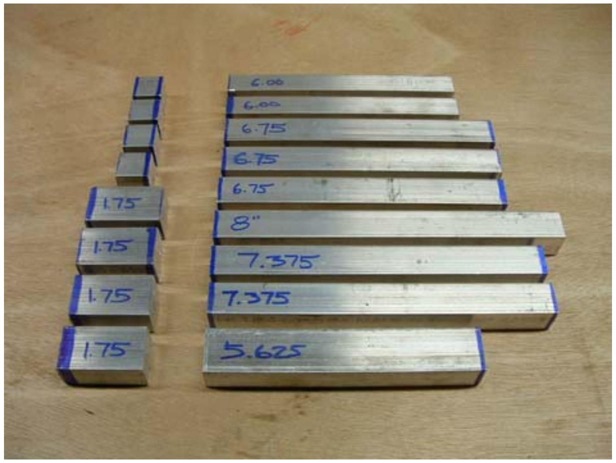




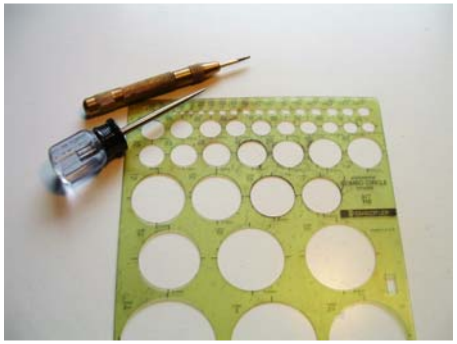


The same hand-cutting technique can be used for all of the metal parts to get accurate cuts with a simple hacksaw. Cut all of the aluminum and steel parts to length. To stay organized, as each part is cut to length, write the dimension of its length on it with the marker. It is also helpful to write the part name.

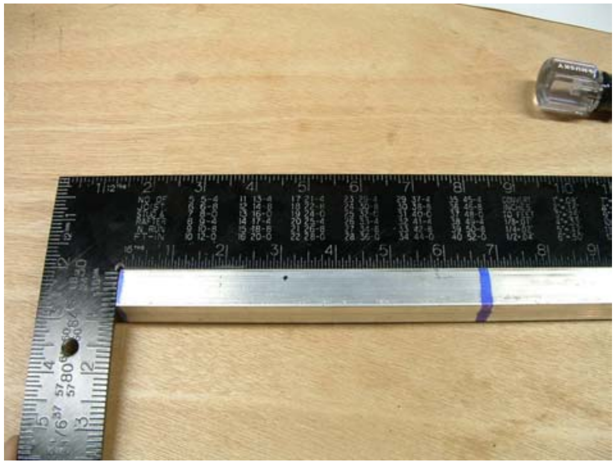
Keep the parts organized. There will be a lot of parts by the time you are done, so it pays to keep things organized with some sort of system so you don't start mixing pieces up.



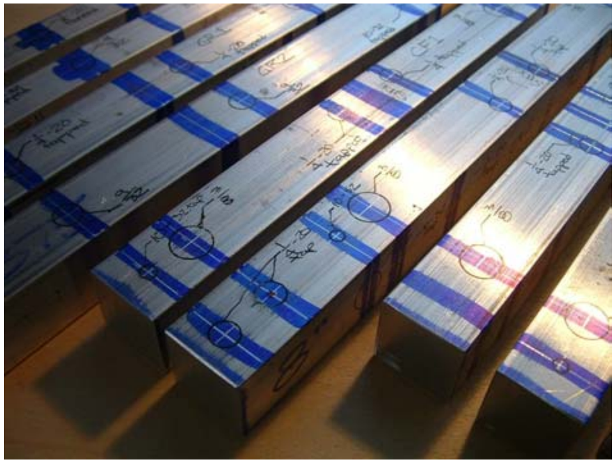
After all of the metal parts are cut to rough length, file the ends clean. Clamp the piece in the vice with the end face up, using the soft jaw covers, and carefully file the end faces flat. Be careful to keep the file horizontal, and only file deep enough to get below the marks from the saw blade. It is better to err on having a part slightly too long than too short, so be sure not to file too far, even if it means leaving an end face with some saw marks remaining. File a slight chamfer on each end face edge to remove any sharp burrs.



To mark the locations of the holes to be drilled on the parts, I used the 6" engineers scale, felt tip marker, a circle template, the scratch awl, and a fine tip felt pen. This pen I used is a technical pen in an .03 tip width. A carpenters square works well on the longer parts. It ensures that you are accurately measuring from the end face. Be cautious if using a carpenters square. While some edges are marked in traditional 1/8", 1/16" or 1/32" divisions, others may be marked in 1/10" or 1/12". This can cause serious errors in marking if not careful.



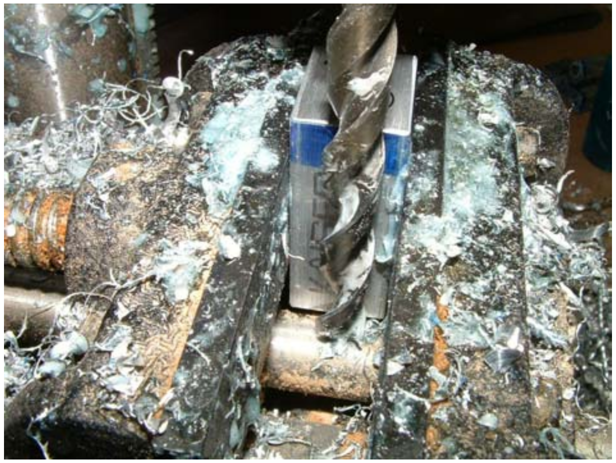
Use the felt-tip marker to color a zone on the part where the center line of the hole is located. Measure and scribe a fine line across the part at the center of the hole location. Also scribe a line at the side to side distance to create a scribed crosshairs at each hole location. Scribing the line that runs parallel to the length of the aluminum parts may be difficult due to marks in the surface from the extrusion process. These might pull the awl into them and create an inaccurate line. If this happens, just color back over any inaccurate scribe lines and try rescribing. Use the circle template, lined up to the scribed crosshairs, to draw the outline of the hole with the fine felt-tip pen. Also write the diameter of the hole directly on the part to avoid having to consult the drawings later to determine what the hole size was (and the inevitable potential errors). With everything clearly marked on the part you will not have to do any thinking when drilling the holes. Mark the tapped holes in a similar manner.



A drill press is highly recommended to achieve the necessary accuracy when drilling holes. It really is indisepensible, and they can be purchased quite inexpensively if you do not own one. Make sure it has enough travel and throat clearance to handle all of the drilling requirements. A drill press vice of some sort is also very helpful. My drill press was a very inexpensive homeowners quality, equipped with a compound cross slide vise. Take some time to adjust the drill press so that the table is exactly perpendicular to the quill.

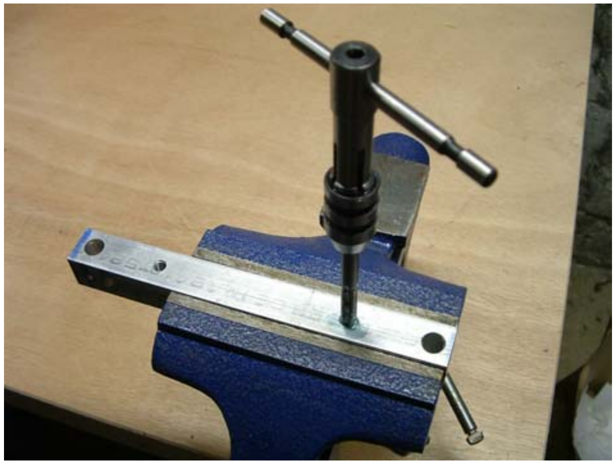
When drilling, especially on the aluminum parts, always use a proper cutting fluid. Drilling aluminum dry will quickly ruin the drill bit.

Try this clamping method when drilling long holes through the length of a part, such as the bearing block shown at the right. Extend the drill press quill down alongside the part. Push it up against the drill bit while clamping it in place. This will ensure that it is parallel to the length of the bit and quill travel.

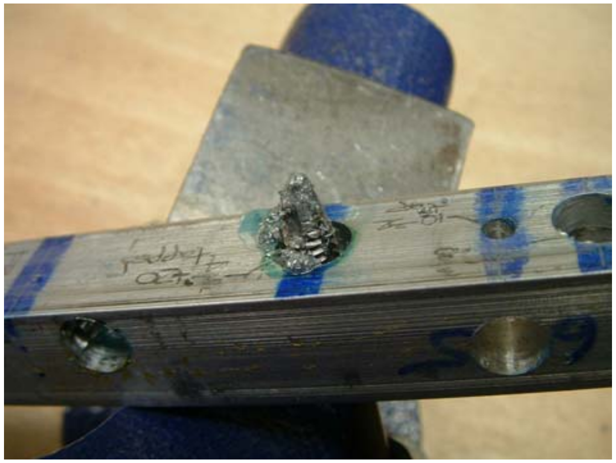


version 1.2

Clamp the parts to be tapped firmly in a vice (use the soft jaw covers, not like I am doing here). Secure the tap into the tap handle and start it into the hole. Be sure to use plenty of tapping fluid that is designed for tapping aluminum. Using tapping fluid is crucial. Taps will not last long when tapping aluminum without it, especially the smaller sizes, possibly not even making it through the first hole.



If you have never tapped a hole before, I highly suggest doing a trial run on an extra piece of aluminum. Use the properly sized drill bit and drill a few holes to be tapped 1/4-20. It is worth getting used to the experience on a scrap piece, as taps can be quite fragile. Any side loading can immediately snap them off, as can excessive chip loading in the flutes. A broken tap can be nearly impossible to remove from the part in the home shop, so a tap broken off in a final part will most likely require starting completely over with a fresh piece of stock. Better to break a tap in a piece of scrap. That said, with the proper technique and a good lubricant, tapping holes in aluminum is quick and easy. I also recommend tapping all of the 1/4-20 holes first, to get comfortable with the technique, before attempting the 10-32 holes. The smaller tap size is less forgiving of error and will break much easier.



Turn the tap into the hole and as it starts to bite, check the alignment. Look at the tap from both the front and the side to make sure you are going exactly perpendicularly to the part. The only opportunity you will have to make any correction is during this first partial turn of the tap. Even then, the amount of correction possible is minor. Taps are very brittle and cannot withstand ANY side loading. As the tap is threaded into the hole, stop every turn or so and back the tap out slightly to break the chips before going deeper.

When the tap comes out of the backside of the hole, clean the chips off of it with a spray lubricant before threading it back out of the hole.

With the tap removed, clean it thoroughly of all chips before starting the next hole.

version 1.2
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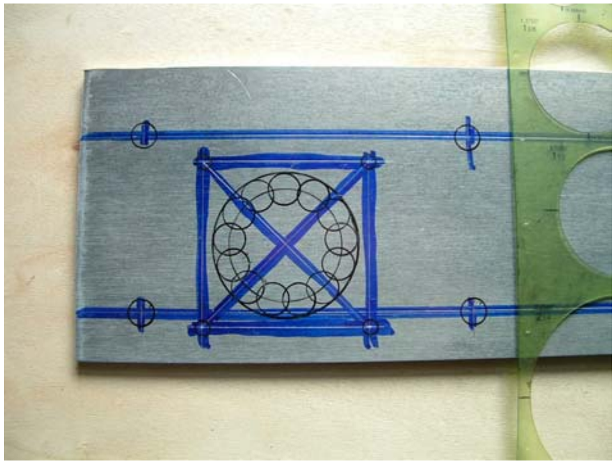
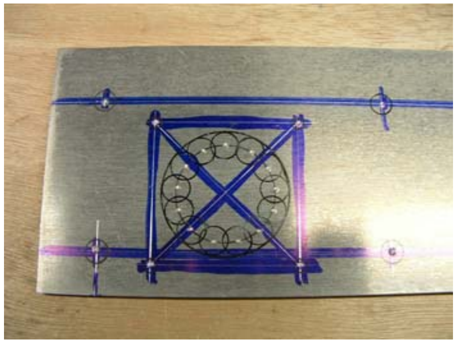
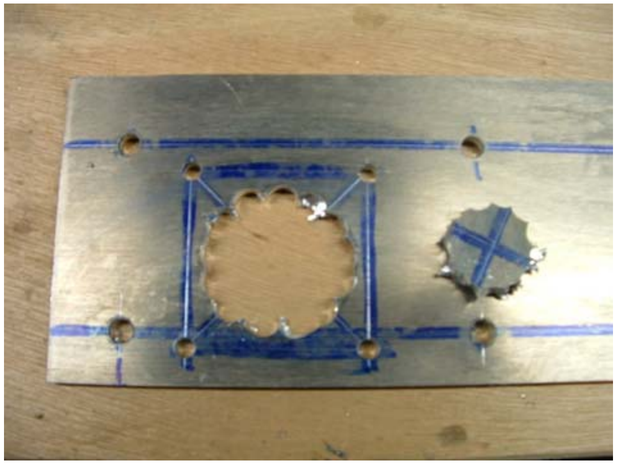
There are a couple of holes during the build that would require a very large drill bit or hole saw. I used the following technique to avoid this. Basically I drilled a series of closely spaced holes, that just slightly overlap, around the inside circumference of the hole. This removed a plug of material from the center. The hole can then be filed to its finish size.



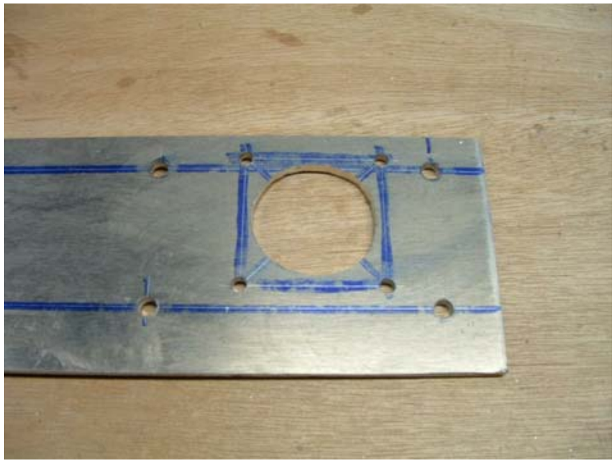
Centered within the hole to be cut, use a circle template to draw a circle that is smaller in diameter than the large hole by the diameter of the drill bit you will be using. For example: for a 1.5" dia finish hole size, using a 1/4" drill bit, draw a 1.25" circle. Make sure this is concentric with the final hole. Then using the template, draw a series of slightly overlapping 1/4" holes as shown in the photo to the right. I spaced these by eye. Center punch a mark at the center of each hole as shown to the left. Drill the series of holes to remove a plug of material as shown.





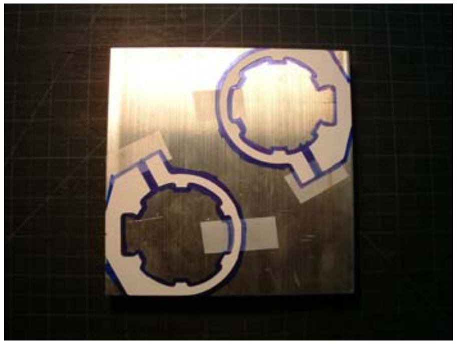
The diameter of drill bit to use for this is somewhat of a compromise and will take some judgement on your part. The smaller the diameter drill bit that you use, the less material you will need to remove later with the file, and hence the quicker this will go. However, the smaller the diameter the bit, the more difficult it is to drill sequential holes that just overlap the previous holes. A larger diameter bit makes it much easier to accomplish this overlap but requires more material removal with the file. This may take a bit of experimenting to find a drill bit size that works best for you. Generally, the smallest that will allow you to still drill holes that just overlap the previous ones. I tend to use a bit around 1/4" dia. If in doubt, err on the size of a larger bit, going up to a 3/8" bit, which is the size that was used in these photos. Filing is not difficult, just time consuming.

If the holes do not overlap, it may be difficult to remove the plug from the center of the hole. A small cold chisel can be used to cut between the holes. Alternatively, you may be able to pry it slightly askew in the hole. Aluminum has a low fatigue life, so a few bends back and forth of the plug inside the hole will usually break it free.



Clamp the part in a vice and use a half-round file to file out the final hole size.

version 1.2



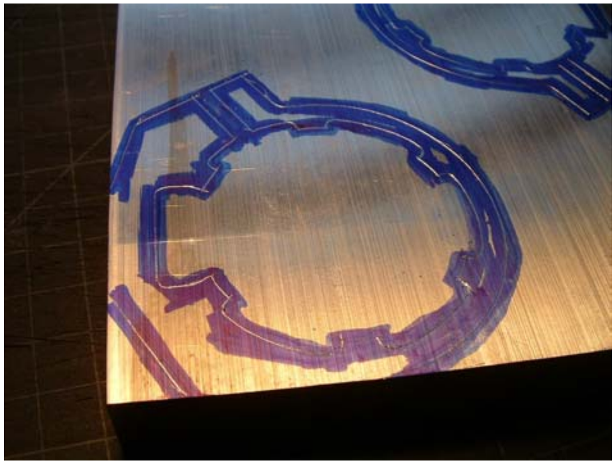
NOTE:
The parts depicted in these photos are an older version of the router clamps and so do not correspond to the current part drawings. These are illustrating the general fabrication technique only.

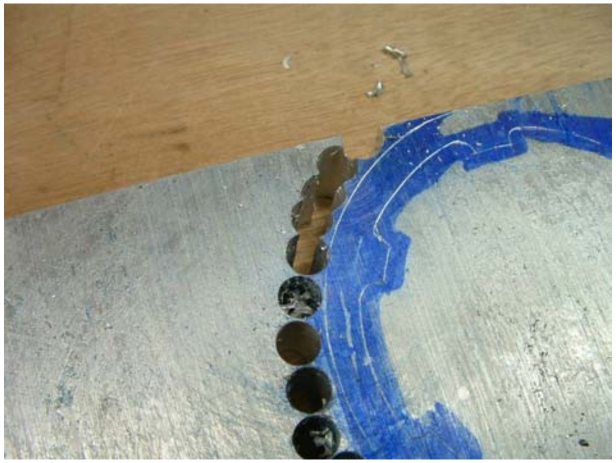
The router clamps are cut from aluminum plate, which can present a bit of a problem to cut them out. A metal cutting bandsaw would be the ideal solution, but most home shops don't include this piece of equipment. My method around this has been a technique that is similar in principle to that described on the previous page for cutting large holes in thick sheet material.

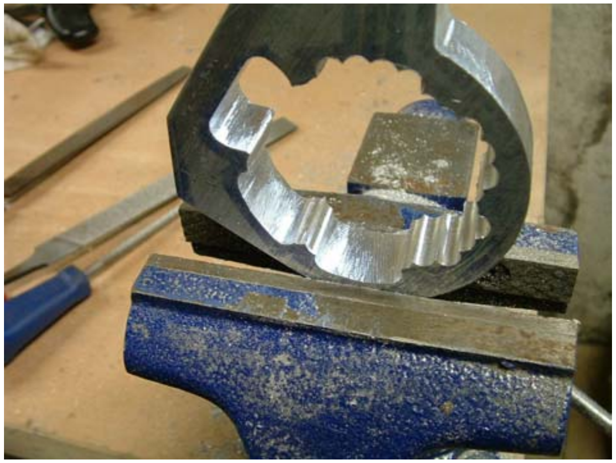
Here, however, choosing an appropriate size drill bit is even more crucial. The same basic compromises are at play: a large drill bit is easier to overlap holes but leaves more material to file, while a small bit leaves less clean-up with the file, but is difficult to overlap holes. However, the stakes in higher with the thicker material. More material to file away will take considerably longer than it would on thinner material. Similarly, incomplete overlap of holes can create a situation where the part is much more difficult to free from the stock. This problem is compounded by the curved arrangement of cutting holes, which makes getting a hacksaw in there difficult or impossible. Ultimately I would advocate a larger bit rather than smaller. While this leaves more material to file, it gives more ability to maneuver a hacksaw around a curve. After the part is free from the plate, you can also use the hacksaw to cut the sharp "ears" down closer to their root, removing some of the material that you would otherwise have to file.

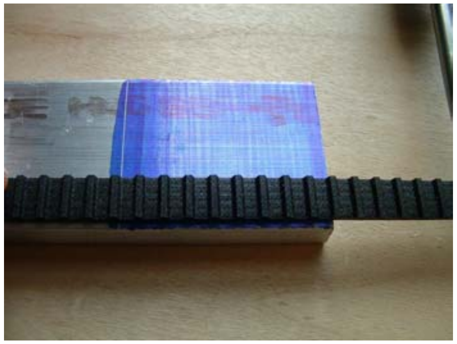
These pieces are relatively complex in their geometry, so this is the one time I advocate printing out the drawing sheet and using it directly as a pattern. If you feel comfortable directly marking out the part outline on the plate without a pattern, then by all means do so. If you choose to print patterns, print out the drawing sheet for these parts on index card stock or cover stock. This is heavy enough to be durable as a pattern. Carefully measure some of the longer dimensions to see if they are accurate to size. Adjust the scaling factor of your printer if necessary to achieve this result. Printing at 100% does not necessarily guarantee this result on paper. Unfortunately it is often off by less than 1%, which is enough to cause a slight inaccuracy but not enough to be able to correct through the printer driver. When you have printed as accurate a pattern as possible, carefully cut it out with an Xacto or utility knife (a knife with a fixed blade is easier to cut curved lines, as the blade will wobble less than those of a retractable knife blade).

Mark the plate with a felt tip marker and tape the patterns to the plate to scribe around them. Due to possible printing inaccuracies, as well as inaccuracies in tracing around the pattern, be sure to leave a little extra material around the faces that will contact the router body. File these into shape slowly and check often against the router itself.

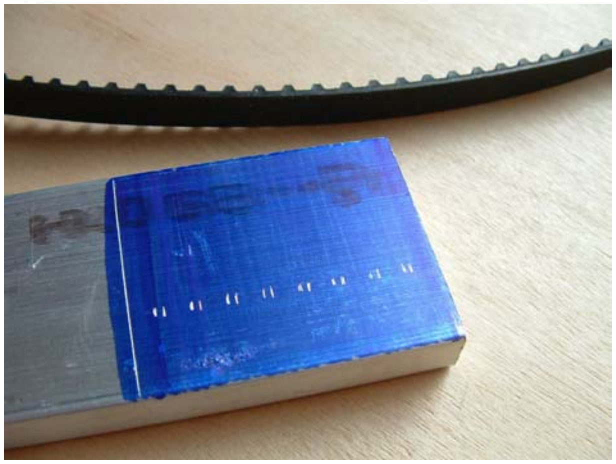




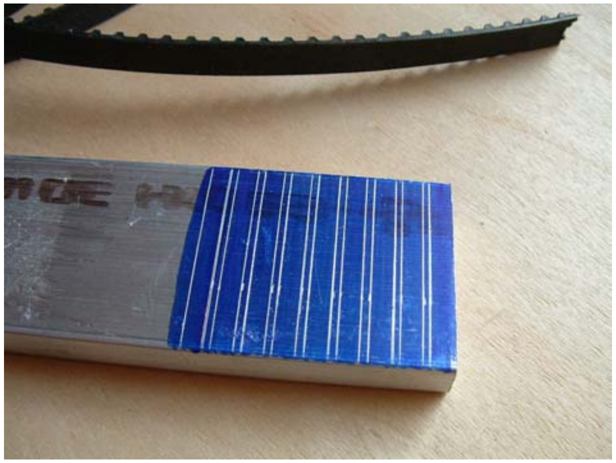




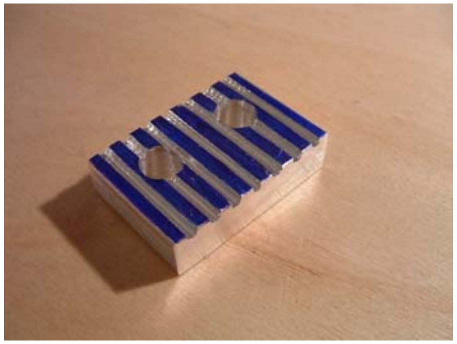
The drive belts are secured with fabricated clamps that have corresponding grooves cut into them. This can be achieved with a simple hacksaw and some patience. No filing was done in any of these photos, this was all done with just the hacksaw.

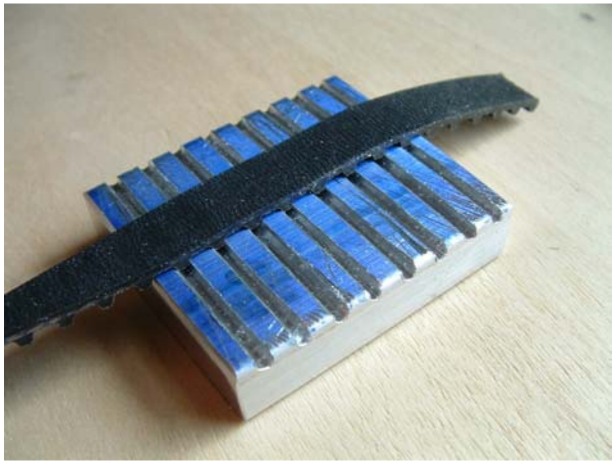


Hold a length of the belt securely on the piece of stock to be marked. Scribe short marks that align with the width of the root of the belt teeth. As you move along the belt marking teeth, move your head as well. It is important that you are looking exactly straight-on at the belt while marking to avoid parallax error.



With the teeth widths marked, use the small carpenters framing triangle to extend the scribe lines across the width of the stock. With the stock firmly clamped in the vice, slowly begin to use the hacksaw to cut out the grooves. The technique here is to keep the saw as horizontal as possible and use a finger or two as a guide against which the side of the blade rests. Think of the saw blade as a long narrow file. Don't be afraid to tilt the saw to the side to widen the slot if necessary. Another technique can be to install two blades in your hacksaw handle. This will effectively create a wider blade that may more closely match the width of the grooves.





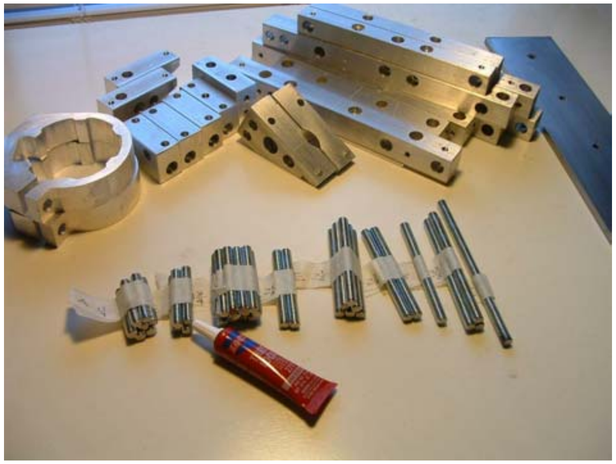
Realistically, since there is clamping force involved during the assembly of the belt into these parts, the depth of the grooves does not have to be the full tooth thickness. More important is that the center to center spacing of the grooves matches the belt. As long as there is some small amount of groove it should prevent any belt slippage once clamped together.

I found cutting these grooves to be much easier than it looks. However, if you just can't get this to work then another method is to cut a short length of belt, flipped over so its teeth mesh with the teeth of both ends of the belt, and just clamp it between two flat pieces of aluminum. This will put the belt out of ideal alignment, but probably not enough to cause problems. However, note that this would rely strictly on friction from clamping force, rather than mechanical engagement.

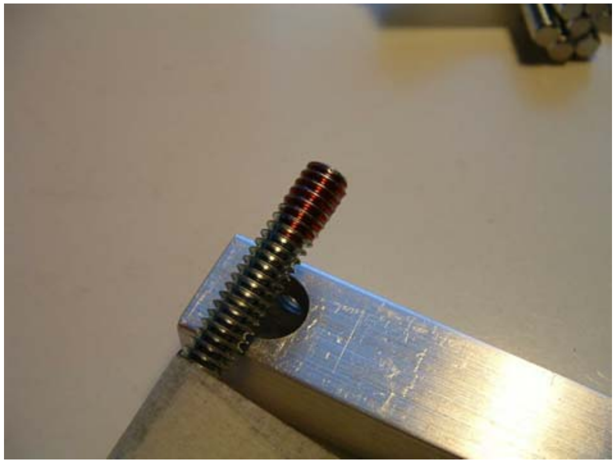
version 1.2

Gather all of the metal parts together. Locate all of the parts that have studs threaded into them. If you have not done so, cut all of the required studs to length. Make sure that the threads on all the parts are clean and free of any oils, tapping fluids, etc. Clean the parts if necessary. Cotton swabs can be used to reach into the holes.

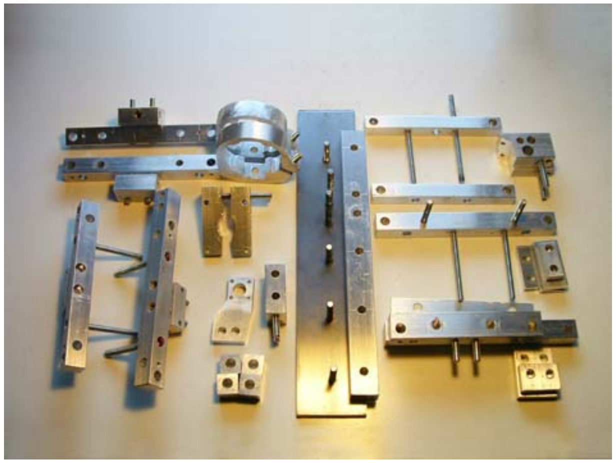
You will be adhering the studs into their holes with a threadlocking compound so that they will not turn when nuts are tightened onto them. Since it can be very difficult to remove these studs once they are bonded in place, I would highly advise doing a trial assembly of everything at this point. It will both allow you to make sure all of the stud lengths are correct, as well as generally familiarizing yourself with how everything goes together.



Following the exploded-view drawings, thread the correct studs into the parts. The stud lengths are calculated for 3/8"-1/2" thread engagement. Plain nuts can help with a trial assembly, as the final nylon-insert locknuts will simply cause the stud to turn deeper into the part. With all of the studs temporarily in place, follow the directions on the following pages to do a trial assembly. Some steps may obviously be omitted, such as those instructing on alignment, or bearing installation. If you wish to install bearings at this point as well to see how everything fully assembles, then go ahead and do so. Just bear in mind that you will immediately be taking them back apart again. If all seems to assemble together correctly, disassemble the parts, staying organized with which studs go into which holes.

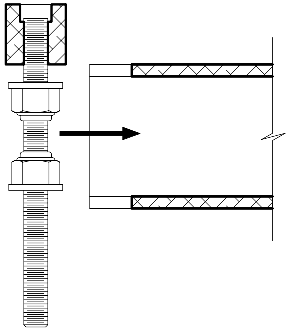


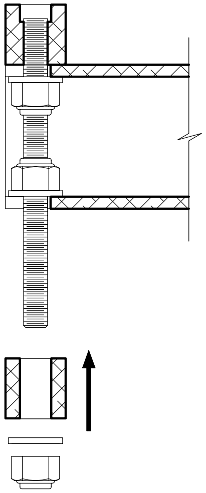
Apply a couple of drops of permanent threadlocking compound to the end of the stud. It does not take much, a couple of drops is plenty. The tip of the tube can be used to spread the compound around the circumference of the stud. Be careful not to squirt more out when doing this. Thread the stud into the hole to the required depth. Set the parts aside to let them dry. Leave them undisturbed for a full day before beginning any assembly. I laid them out to dry arranged with their neighboring parts, anticipating assembly.



If any of the studs need to be removed for any reason, it can be done. Adjust a pair of vice-grip type pliers to clamp tightly to the stud. Remove the pliers and put the part into the oven, set at 400 degrees. Heat it for about 5-10 minutes after the oven has come up to temperature. Carefully remove the part from the oven. If at all possible, clamp it in a vice while using the preadjusted vice-grips to remove the stud. Once the part has cooled, chase the threads with a tap to remove threadlocking compound residue before installing a new stud.

version 1.2





As per the diagram to the left:

Thread a locknut, with a flat washer above it, onto each of the studs in part # 03, marked “gantry left top”. Thread the nuts nearly to the top, leaving about 3/16" of an inch between the washer and the part.

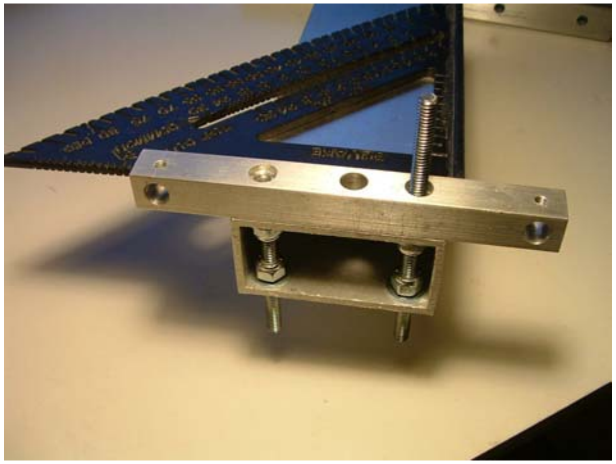
Thread another set of nuts onto the studs, this time with the nylon insert going on first. Essentially these are being threaded on backwards. To do this, you might need to thread the nuts on the conventional way first, perhaps even a couple of times, so that the stud forms threads into the nylon insert. Even having done this, it may be difficult to get the nuts threaded on straight. Use caution and do not force the nut onto the stud with a wrench if it is not going on straight. Try another nut if necessary. Thread these nuts up the stud so that they are about 1/2" below the first set.

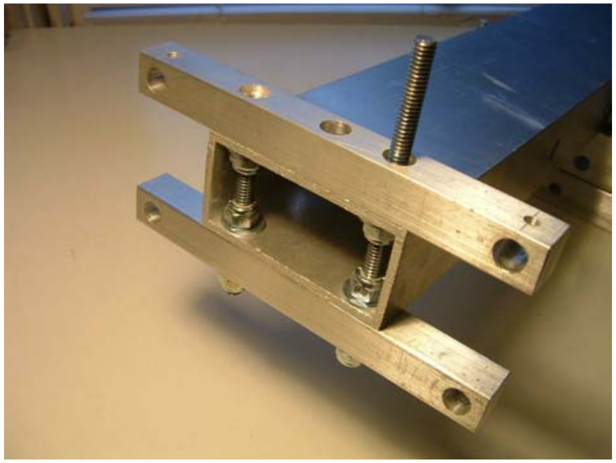
Slide a flat washer up each stud so that it is against the inverted nuts. This assembly should now slide into the slots on the left side of the gantry, and generally look like the arrangement in the top photo at the right.

Using the framing triangle, as shown in the top photo, hold the inserted part so that it is perpendicular to the gantry. Tighten the top set of nuts, being careful to keep everything perpendicular.

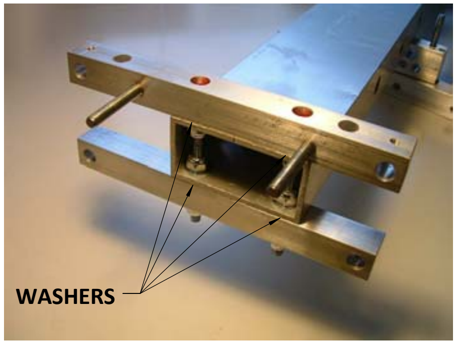
Next, thread the inverted nuts back down the stud so that they are just putting a little bit of pressure against the bottom inside face of the gantry tube. The purpose of these nuts is to keep the gantry tube from being crushed under the pressure of tightening the left bottom part.

With the lower nuts in contact with the inside of the gantry tube, slide part # 01, gantry left bottom, up the studs. Using the triangle to make sure it is also perpendicular to the gantry, install another set of flat washers and locknuts to hold it in place. Tighten them securely.

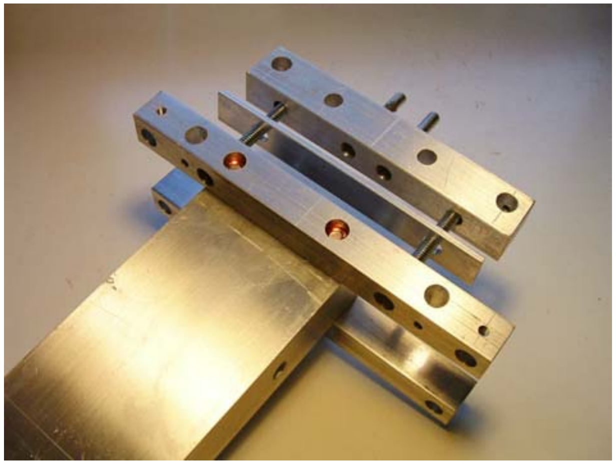




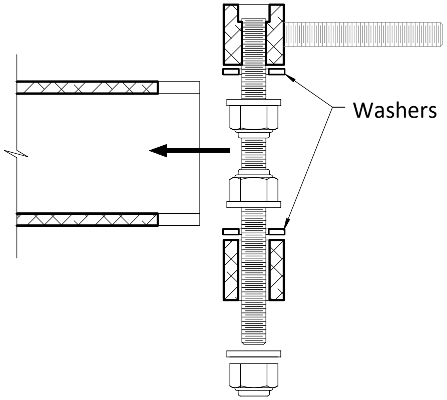
version 1.2



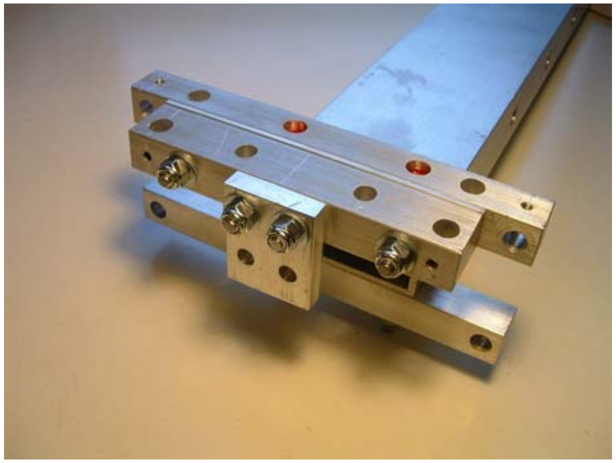
The right side of the gantry uses the same basic configuration of nuts and washers to secure parts #12 and 13 (gantry right top and gantry right bottom) to the gantry tube, with the addition of four extra washers. Washers are used to space parts #12 and #13 a distance of 1/16" away from the gantry tube. Consult the diagram at the left center, as well as the exploded view drawing on page 27 for clarification. They do not show up clearly in these photographs. Use the square again to make sure the parts are perpendicular to the gantry tube.



The two studs on the side of part #12 should be facing away from the ganty tube. Slide part #11 (gantry spacer) and part # 10 (gantry outer right) onto the studs. Note that part #10 is not quite symmetrical and it is possible to accidentally install it upside down. When it installed in the correct orientation the vertical hole at each end of it should align exactly across to a similar set of holes in part #12.

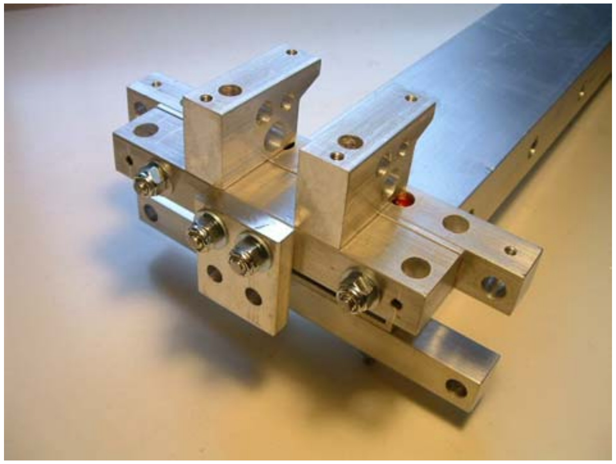


With these parts in the correct orientation, thread washers and nuts onto the studs and tighten to secure them. All 3 of the top parts should be flush across their top faces.



Install part #09 (X belt mount) onto the remaining studs and tighten it in place with washers and nuts.

Install parts # 06 and #07 (Y motor mounts) as shown. Note that these parts are different. The holes for the motor attachment are offest to one side or the other. Look at the photo closely to note which side they face. If in doubt, hold a motor up to the mounts to make sure the holes align.

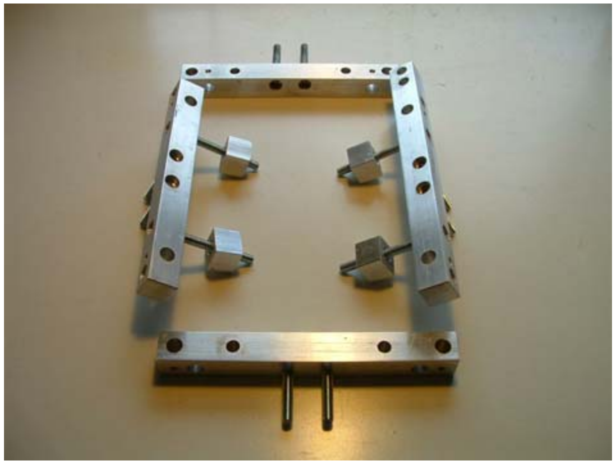


Thread a washer and nut up each stud. Do not tighten then down fully. Tighten the nuts just to the point where the mounts can be moved around by hand.

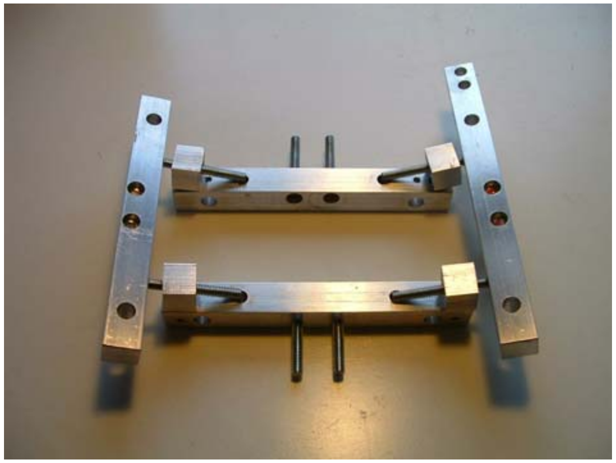
You should now have a gantry assembly that looks like the one in the photo to the left. Set it aside for the moment.

version 1.2

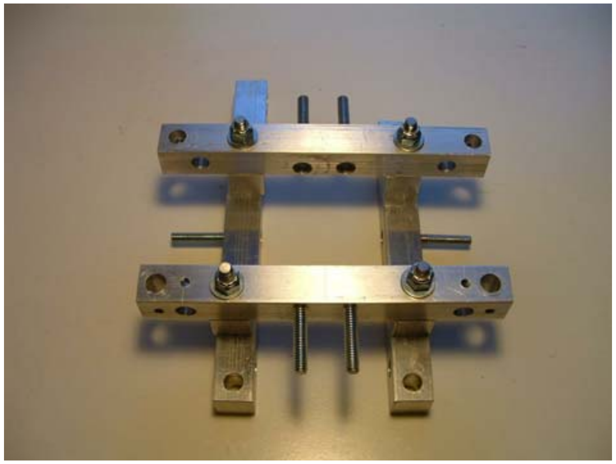
Lay out parts #16 (there are two of them), #22, #23, and the four #24 as shown in the photo to the right.



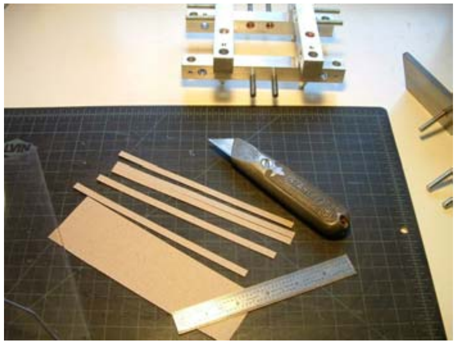
Slide the four spacers up the studs, and then insert the studs down through the two part #16.



Thread a washer and locknut onto each of the four studs from the rear (photo to the right is taken from the rear, with the assembly flipped over). Tighten them just until they are barely snug. They should keep the assembly from flopping all over, yet still allow you to move it by hand.



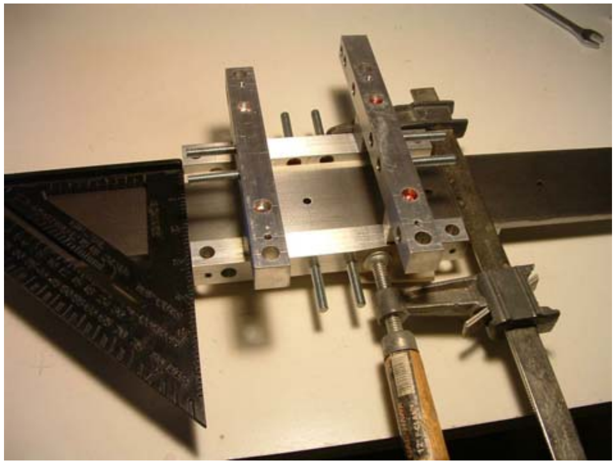
version 1.2



As you have probably noticed, this assembly is one big parallelogram linkage. This next step is basically to get the parts perfectly square, parallel, and with the correct spacing between them. To do this, we are going to temporarily clamp them to the Y and Z rails.

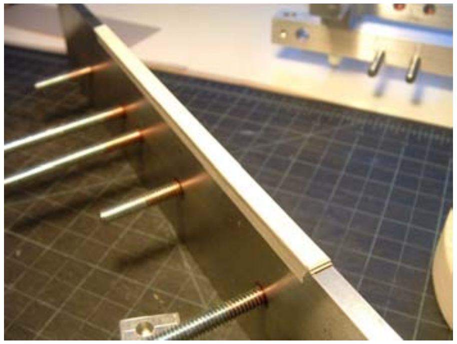
First cut out some thin strips of paperboard. I used 1/32" chipboard (the stff cereal boxes are made of). Tape as many as are needed to one edge of each rail to add about 1/16" -3/32" to its width as shown in the photos to the left.

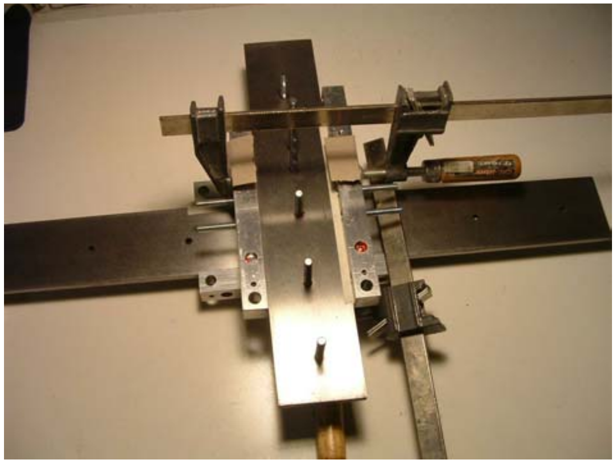
Place the Y rail between parts #16 and making sure they are aligned across to each other using a triangle, clamp them to the rail. (upper right photo)

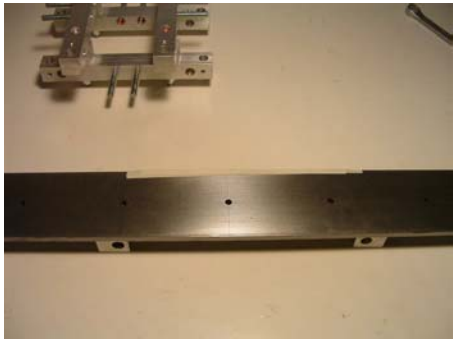


With the Y rail clamped between parts #16, insert the Z rail with its added paper strips between parts #22 and 23. Try to get the bottom ends also aligned across to each other and clamp them to the rail.

Note that there are many possible clamping configurations and you may be able to come up with a way of clamping that works better for you than what I am showing here.



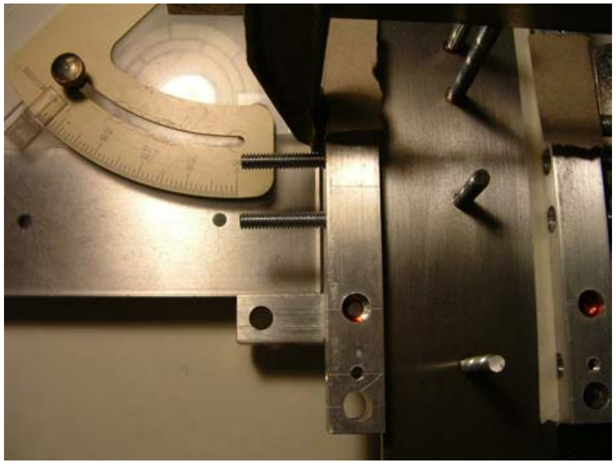




The goal now is to get the two rails as perpendicular to each other as possible and then fully tighten the four nuts on the backside of the studs to securely lock the assembly in place. In the photo to the right I am using an adjustable drafting triangle as a guide. This may take some patience and multiple attempts at loosening clamps, readjusting, etc..

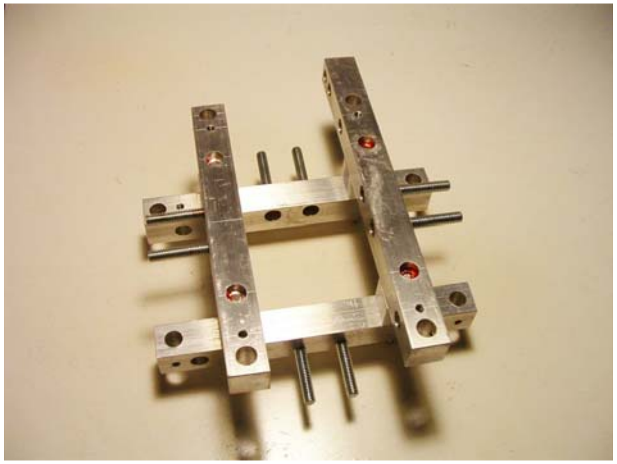
There will be some adjustability in the bearings on which the rails rolls, so if it isn't 100% perpendicular it may be OK. But make every attempt to get it as perpendicular as possible. If necessary, you can disassemble the parts and file out any of the holes if this helps to bring the assembly into a perpendicular orientation.

Once you are happy with how square the assembly is, make sure the nuts are fully tight and unclamp the rails and remove them.

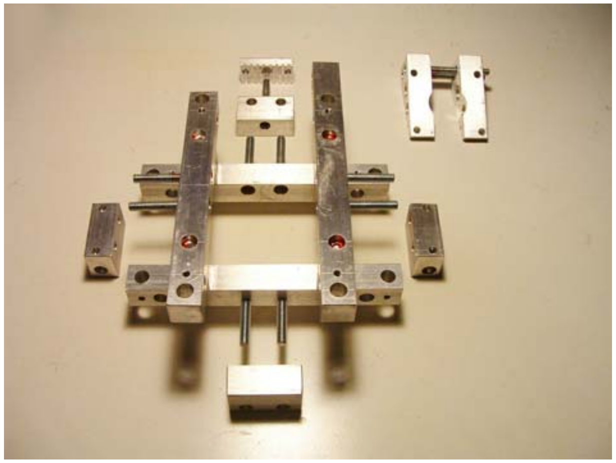


version 1.2

The carriage assembly should now look like the photo to the right. It should be as square as possible, and the spacing between the parallel parts should be about 1/16"-3/32" wider than the rails.

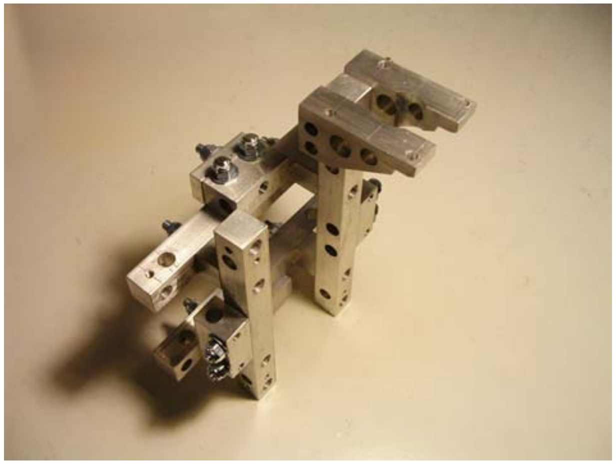


The next step is to attach the bearing blocks (parts #15 and 17), the Y belt clamp (part #18), and the Z motor mounts (parts #20 and 21).

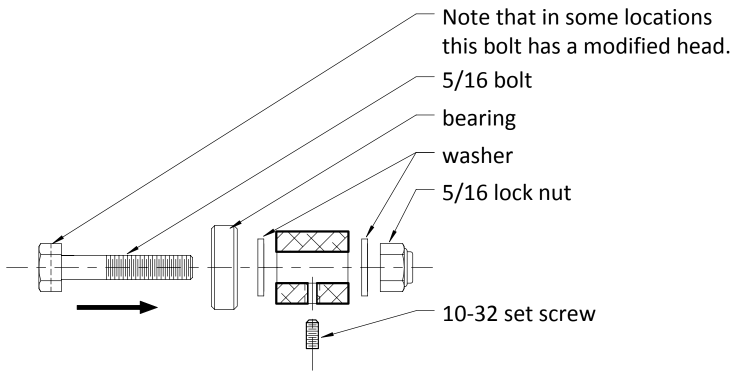


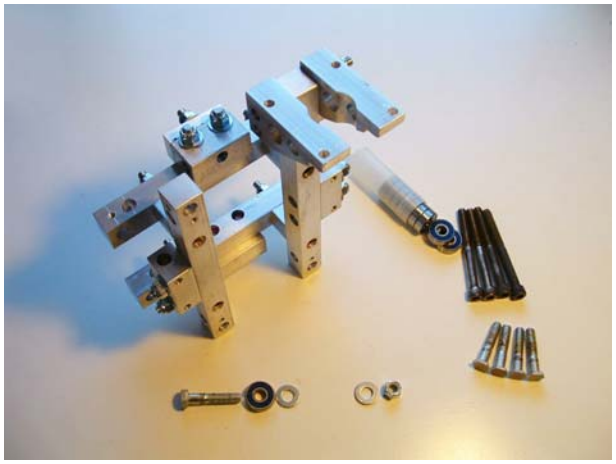
Bolt all of the parts together as shown in the photos to the right and in the exploded view drawing on page 28.

Note that the position of the Z motor mounts will now provide a good way to orient yourself when looking at some of the photos that follow. The assembly is quickly going to become complex looking enough that it may become difficult to tell which direction is which in the photos. The Z mounts are a unique enough shape that they can be used as a directional guide. Also note that the ones in my photos have a couple of additional lightening holes drilled through them, so they may look slightly different than the ones in the plans.



version 1.2





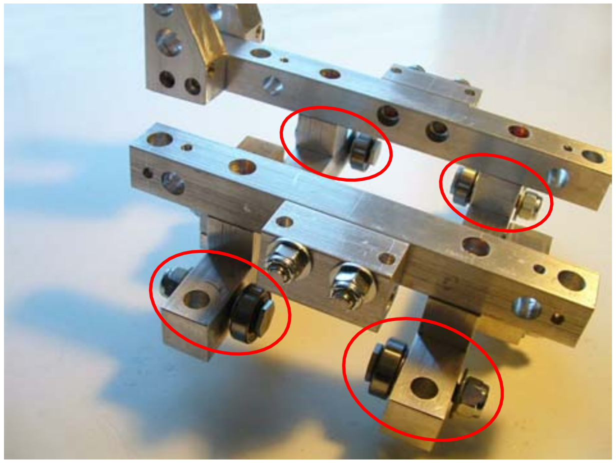
NOTE: In addition to this series of photos, refer to the exploded drawing on page 29 that depicts the bearing locations. It is sometimes difficult to have one view clearly show all of the bearing locations in a given step, so this drawing may help clarify.

Next we will begin to populate the carriage with bearings. Most of the bearings are attached in the configuration of bolt, bearing, washers, and nut that is show in the above left diagram. This sequence of parts is also seen in the lower left corner of the upper right photo.

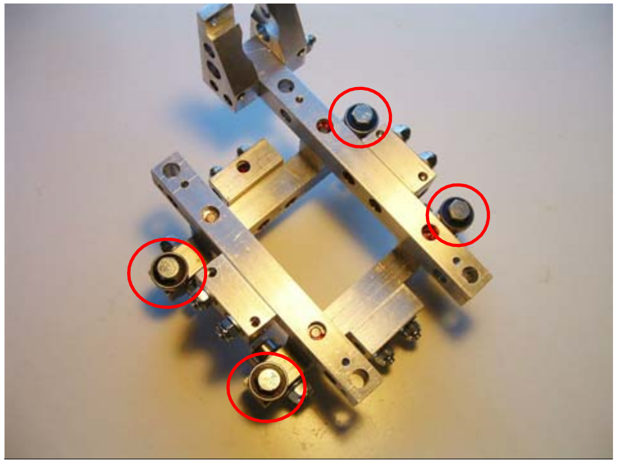
As you install each bearing, thread the locknut on far enough that there is just a tiny bit of clearance between the washers and the part. The bearing should just be able to slide from side to side, but not rock or seem loose.

Again, use the Z motor mounts to orient your carriage assembly to match what is seen in the photos.

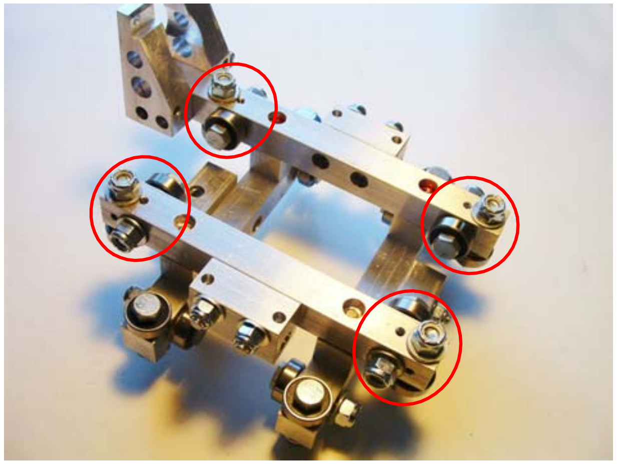
Begin by installing the four bearings that are circled in the middle right photo. NOTE: These four bearings use modified bolts that have had the head thickness reduced for clearance. Standard bolts will not work!

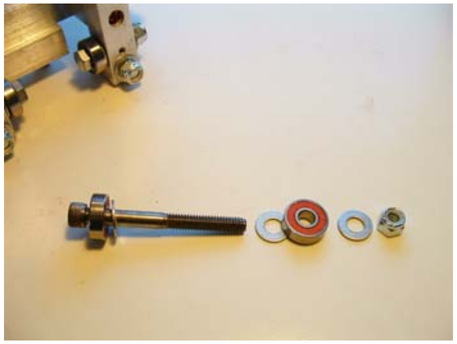


Next install the four bearings that are circled in the lower right photo. These use standard bolts.

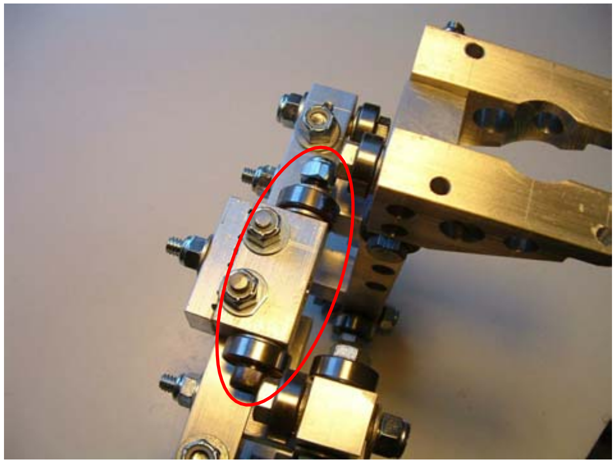


Next, install the 8 bearings that are circled in the photo to the right. Note that there are two bearings at each of the locations that are circled, even though a couple of them are difficult to see in the photo.

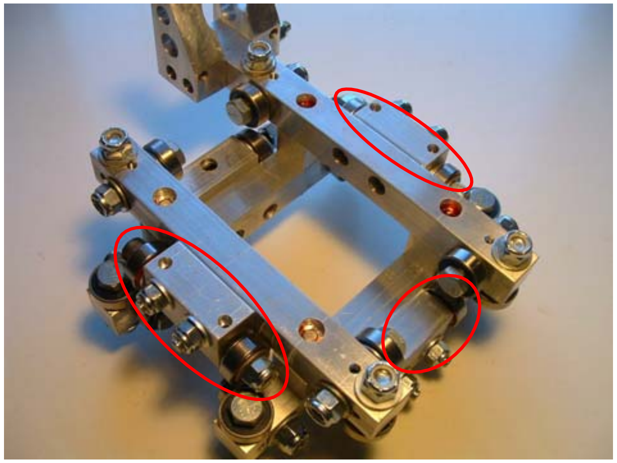




The four bearing block parts have a longer bolt that goes through them, holding a bearing on either side of the aluminum block. The bearing assembly sequence is seen in the photo to the left. Slide one bearing onto the socket head cap screw, and then one washer. Note that there is no washer between the head of the socket head cap screw and the bearing. Insert this through the bearing block. Next slide a washer, bearing, another washer, and then the locknut.



Install in the four locations shown in the photos to the right. This step will install another 8 bearings total, and will complete the bearing installation on the carriage.



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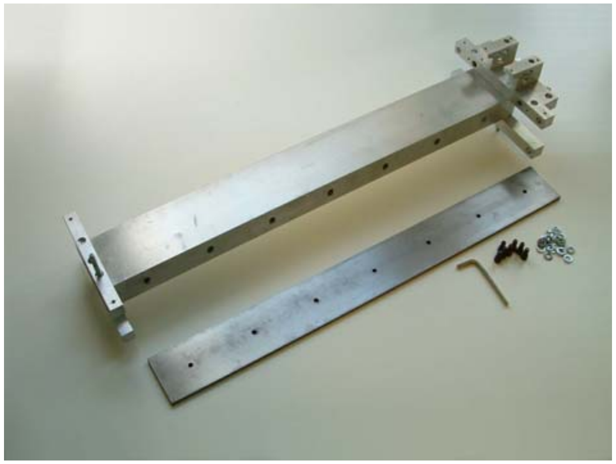
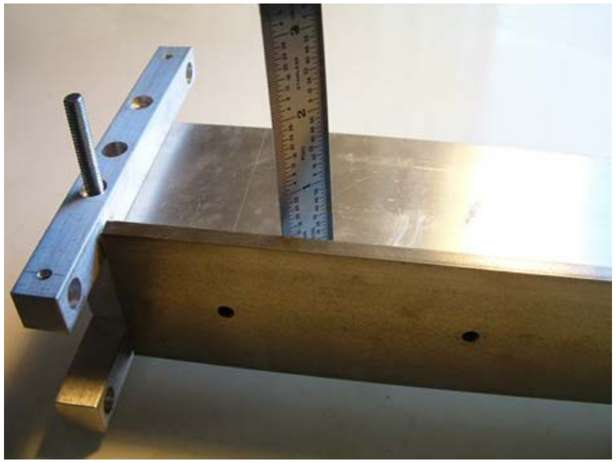
The next step is to install part #14 (Y rail) to the gantry assembly. This is relatively straightforward, using (7) 1/4-20 x 1/2"socket head cap screws. The cap screws need to have full thread engagement in the rail, yet not protrude beyond it or they may strike the carriage as it slides. I ended up simply using two lockwashers under the head of each screw and this resulted in the right amount of thread length.

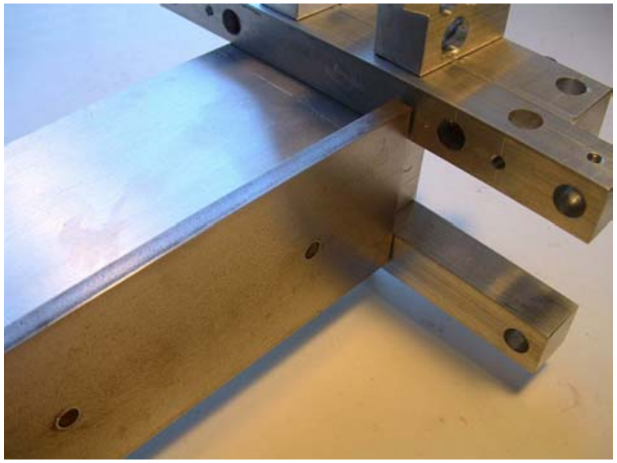


Use a hex key that is long enough to feed the cap screws through the 1/2" holes in the back face of the gantry tube. It may be easier to do this if the front of the gantry tube is facing up. This way gravity is holding the cap screw on the hex key as you feed it up through the holes.

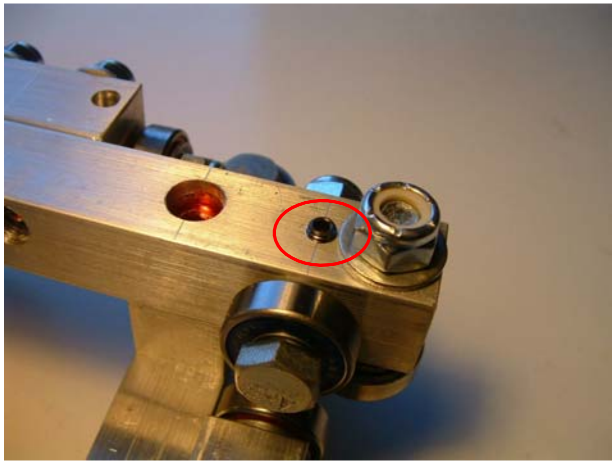
Get all 7 of the screws threaded into the rail, but not tightened fully. Tighten the two outer ones until they are just tight enough that the rail can still be moved around. Use a scale and measure both top and bottom, and at each end of the rail to make sure it is exactly centered on the gantry tube. When it is centered, tighten all of the screws down fully.



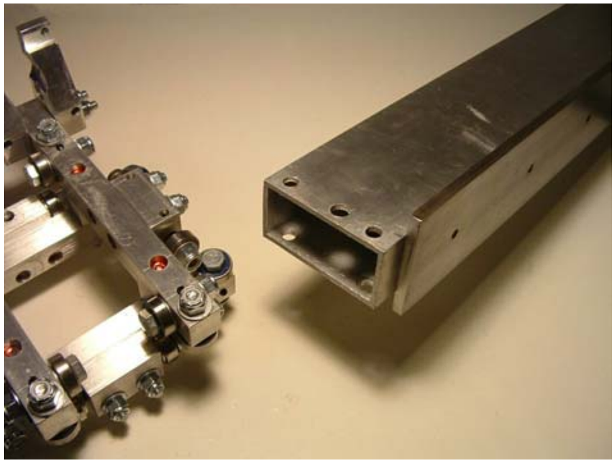
The rail should just fit between the outer gantry parts. If it does not, shorten it as needed by carefully filing some material from the end of the rail. If there is a gap, even up to about 1/4", that is ok.

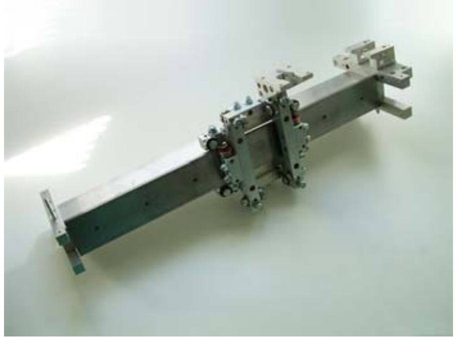


At the location of each of the bearings that has been installed on the carriage, thread a set screw into the hole that is perpendicular to it. For now, just thread these in a few turns so that they do not fall out.



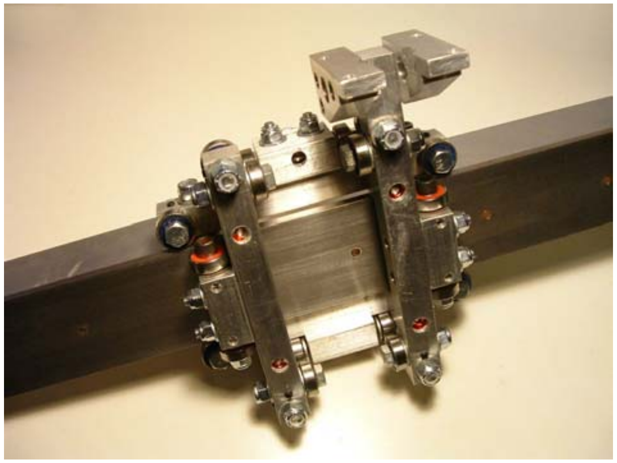
Unfortunately, it is now necessary to temporarily remove the left gantry assembly. It was important to have previously installed it to make sure the Y rail fits properly during its installation. Loosen the nuts on the left gantry assembly as just enough to slide it out of the slots on the end of the gantry tube.



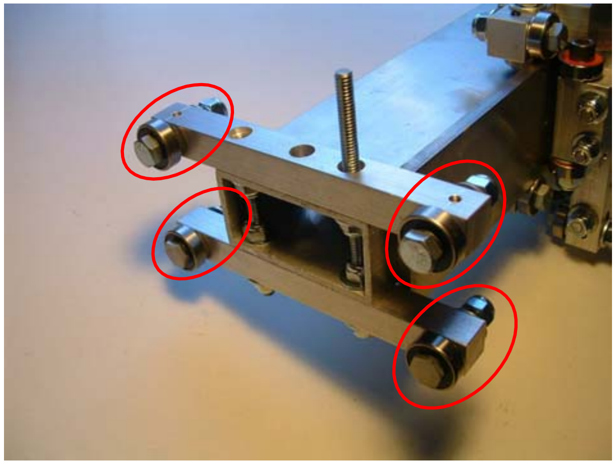


The carriage assembly can now be slid onto the Y rail. There should be enough clearance between the bearings and the rail that is easily slides on. If the bearings do not move far enough apart to allow the carriage to slide onto the rail, stop and investigate why. If you have been inaccurate in drilling holes, there may not be the proper range of adjustability for the bearings. If this is the case, look closely to determine which bearings need to be able to slide further away from the rail. Remove them from the carriage assembly. The holes can then carefully be filed to elongate them, giving more adjustment range.

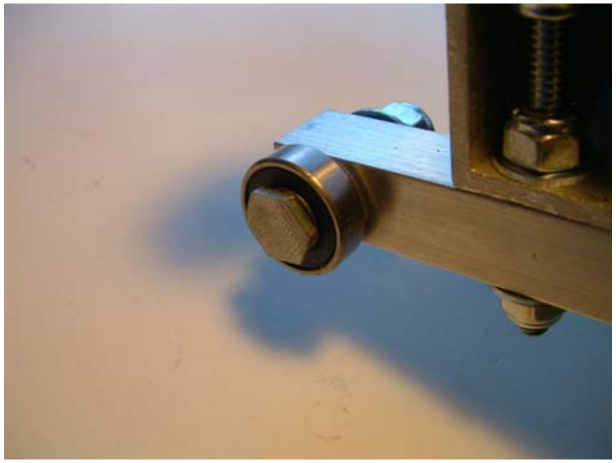
After sliding the carriage onto the Y rail, reinstall the left gantry assembly. The gantry/carriage should now look like the photo to the left. Be careful in handling it, the carriage will slide very easily and has significant mass, which can easily lead to smashed fingers.

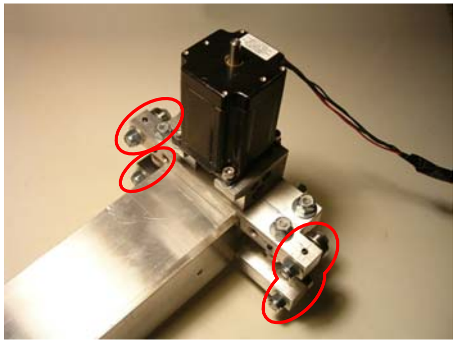


Install the four bearings shown in the locations circled in the photo to the right. Note that the lower two use the bolts with the modified heads, which are necessary for clearance.



The photo to the right illustrates the lower bolts with modified heads.

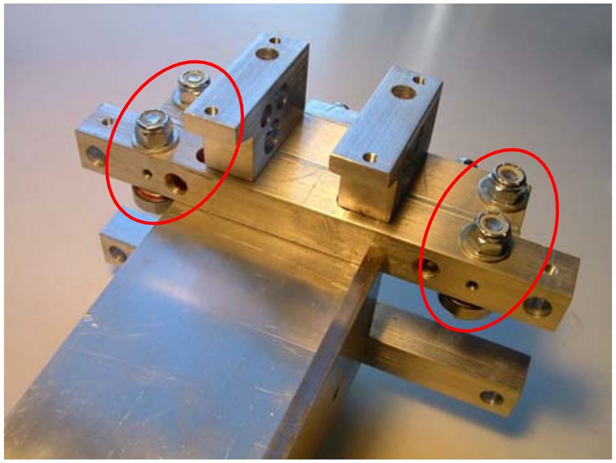




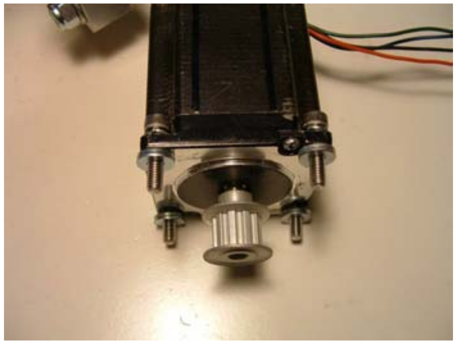
Install the four bearings that are circled in the photo to the right. The two rear ones are difficult to see in the photo, but all four are installed in the same orientation as the two front visible ones.

Install the four bearings that are circled in the photo to the left. Again, the two lower ones are obscured in the photo, but they are all installed in the same orientation.
(Ignore the motor in this photo, it will be installed during the next step)

As was done with the carriage, install a set screw in the threaded holes that are perpendicular to each bearing location.

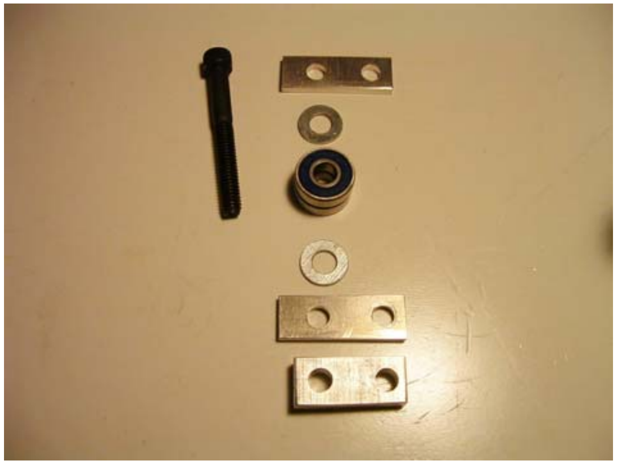


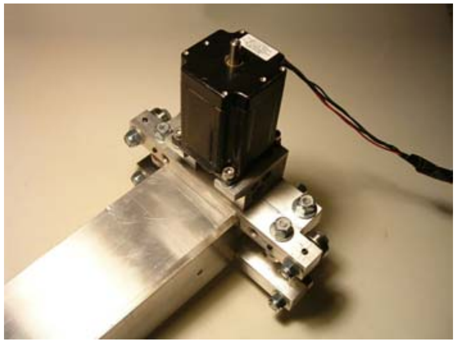
version 1.2



As seen in the left photo, install a timing belt pulley onto the shaft of a stepper motor. How far it is located onto the shaft will probably need to be adjusted later, so just push it on so that it is slid most of the way up the shaft, but not fully touching the motor.
Insert the four #10-32 x 3/4" socket head cap screws and 8 washers as shown. Use enough washers that their thickness is slightly greater than the round boss on the end of the motor.

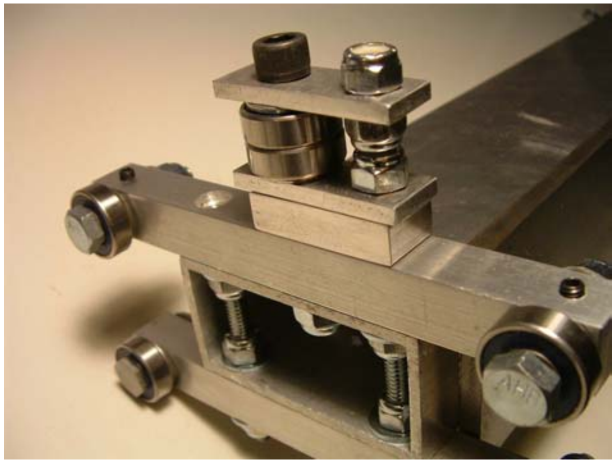
Install the motor to the motor mounts as in the middle left photo. Orient the motor so that it is square to the mounts and tighten the screws.

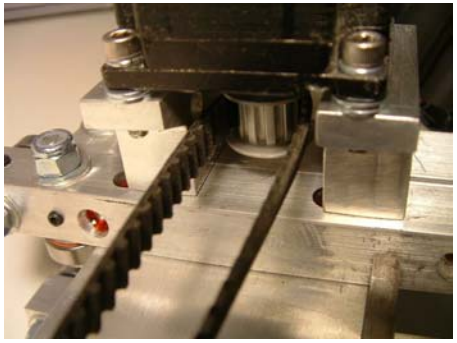




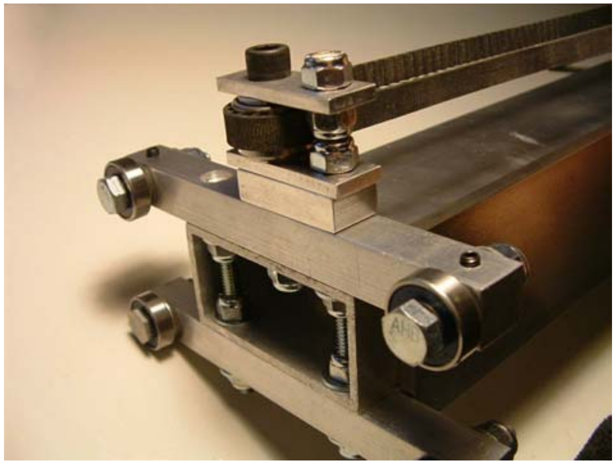
The upper right photo shows the parts laid out for the belt idler pulley assembly. Assemble the parts as seen in the middle right photo.

The nuts between the two flange plates serve the same purpose as the ones inside the gantry tubes, they act as an adjustable spacer. As such, the nut below the top plate is threaded on upside down so that its face is against the plate.





Place a length of timing belt around the drive pulley (left photo) and then around the idler pulley (right photo). In the next step we will trim the belt to length.



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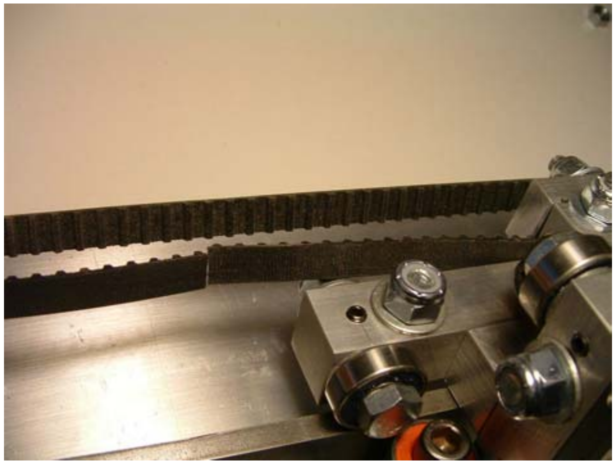
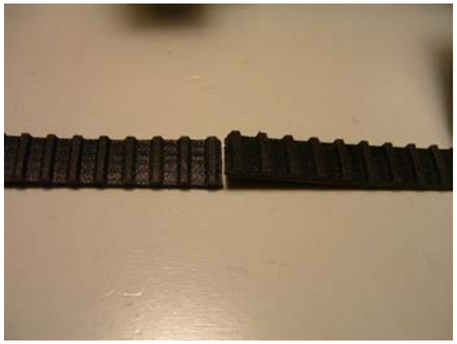
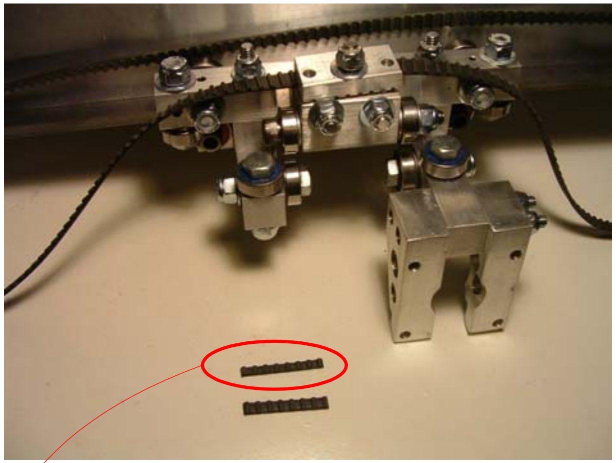
I have found that the easiest way to trim the belt to the correct length is to do the following: Temporarily tighten the belt clamp down to the belt, with several inches sticking out to the left (right photo). Make sure the belt is correctly looped around the drive pulley and idler pulley. Pull the free end of the belt tightly to the end that is clamped. Make sure that the stepper motor is all the way to the left side of the adjustment range that is provided by the slotted holes through which they bolt. Pulling the free end as tightly as possible to the clamped end, note at which tooth it needs to be cut so that it will come together as shown at the right. You should be able to pull the belt with one hand while marking where to cut it with the other. Remove the belt from the machine and cut it to length where it was marked. Cut the belt immediately beyond a full tooth as seen in the middle left photo.

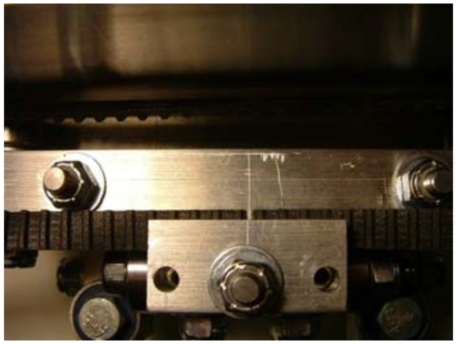




Installing the belt is easiest with the gantry assembly tipped forward on its face. In this position, slide the two ends of the belt up into the clamp as seen in the lower left photo. The belt does not need to be around the drive pulley or idler pulley.

Cut a length of belt to match the length of the clamping area. Slit this belt lengthwise as show in the right photo. Slide this small strip of belt under the clamp from the side opposite the belt. It will be in the area indicated by the red dashed lines in the lower right photo. This acts as a spacer so that the clamp will provide even pressure on the belt when the nut is tightened.

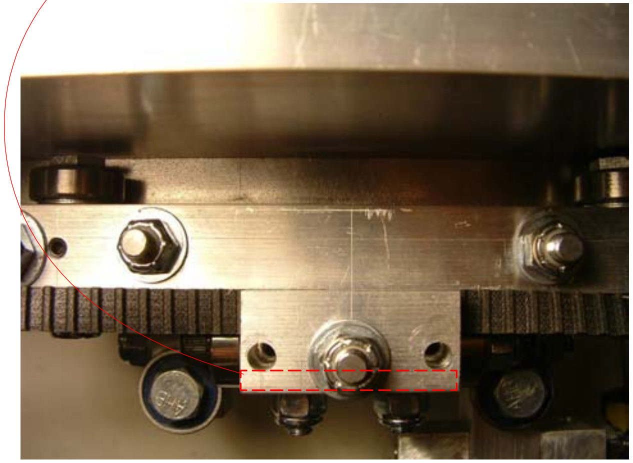




With the small spacer strip of belt in place push the drive belt all the way into position as shown at the right. Tighten the clamp nut down. If the belt is correctly engaging into the grooves on the clamp then the nut will not need to be excessively tightened.

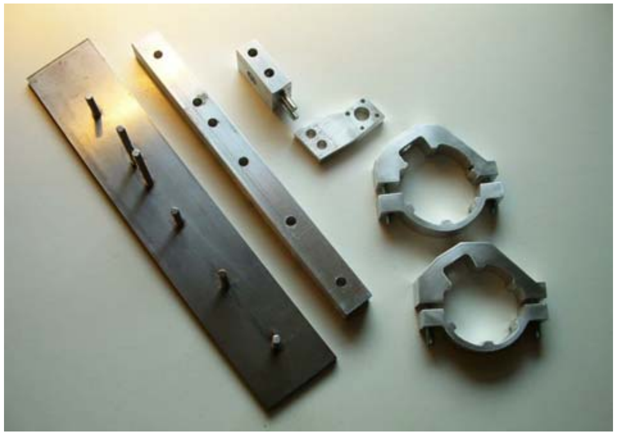
Install the belt first around the drive pulley and then the idler pulley. You will need to temporarily remove the top plate from the idler pulley to install the belt.

If the belt was cut to the correct length, it should have some amount of tension on it at this point. The motor mounts can be slid to right in their slotted holes. Pull the motor as far as necessary so that the belt has an adequate amount of tension on it, and tighten the mounts.



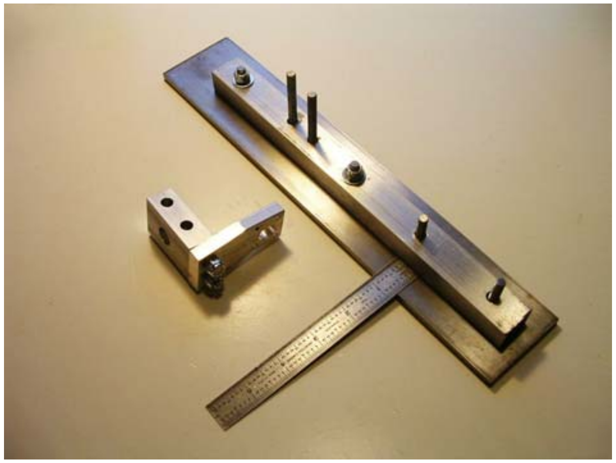
version 1.2

Gather the Z axis parts, #25-#30 as shown to the right.



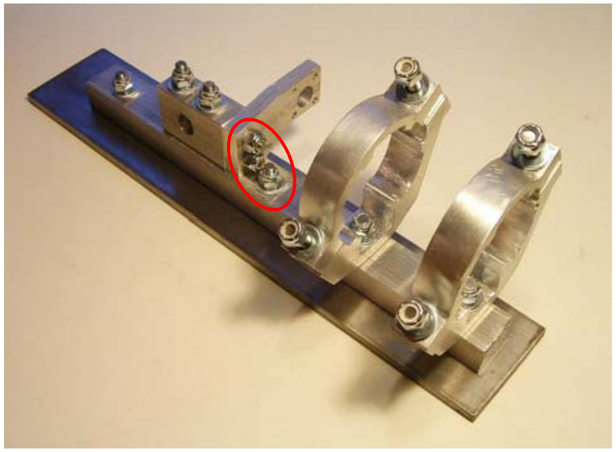
Attach the Z rail block (#26) to the Z rail (#25) with locknuts and washers at the two stud locations shown in the right photo. With a scale, carefully measure along both sides to make sure it is both centered on the Z rail and is parallel. If it will not move into the position needed, carefully file out any holes necessary to allow the rail block to be centered and parallel. When satisfied with its positioning, tighten the two nuts.

Attach the nut plate (#28) to the nut plate block (#27). Note that these two studs are close together which prohibits using washers. Keeping the rear faces of the two parts flush, tighten the nuts so they are just snug.

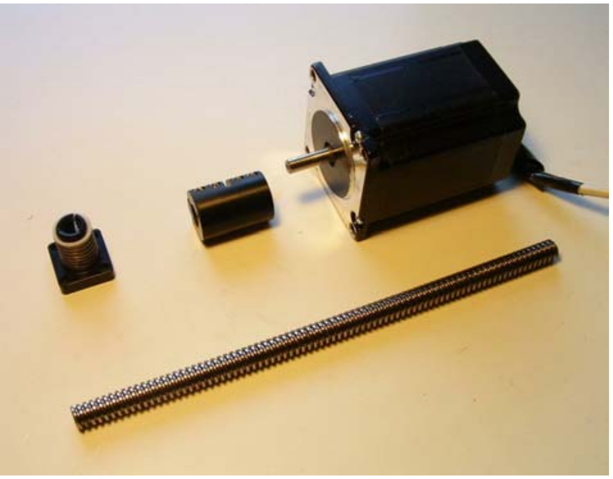


Install the nut block plate to the Z rail block as shown. Make sure that it is also centered and parallel before tightening it down fully. Note that the clearance between the ends of the studs that hold the nut plate and the middle nut on the Z rail block is very tight (circled area to the right). This may necessitate filing the end of the stud for clearance if it protrudes beyond the nut.

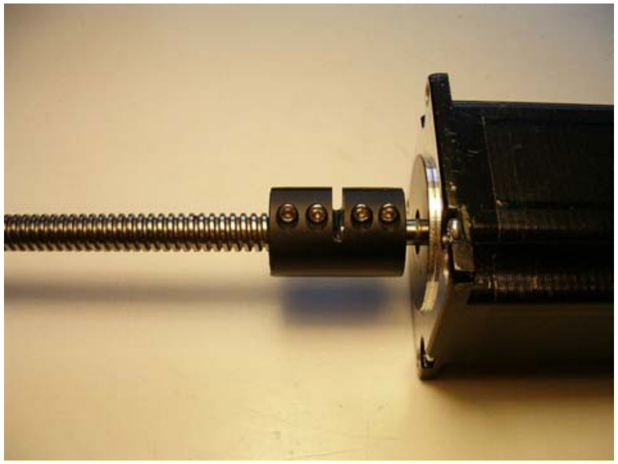
Install the router mounts and clamps as shown.



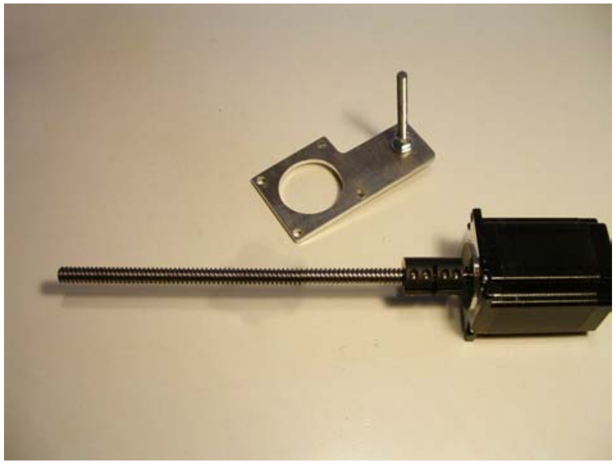
Gather the Z axis motor drive parts as shown to the right.



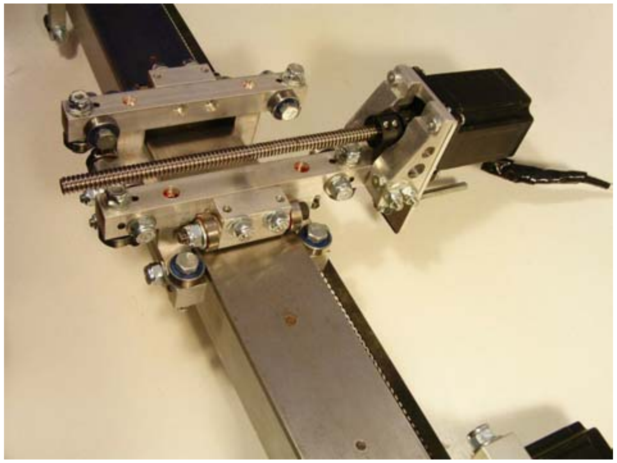
Slide the coupling up the motor shaft so that the end of the shaft is about in alignment with the inside face of the slot in the coupling. Lightly tighten the set screws to secure it. Thread the drive screw into the other end of the coupling, so its end is also flush with the inside of the slot. Lightly tighten the setscrews. There should be clearance bewteen the end of the drive screw and the end of the motor shaft that is equal to the width of the coupling slot. Fully tighten the set screws. Note that the derlin material is very grippy, so do not overtighten the set screws. They should hold securely with little tightening.



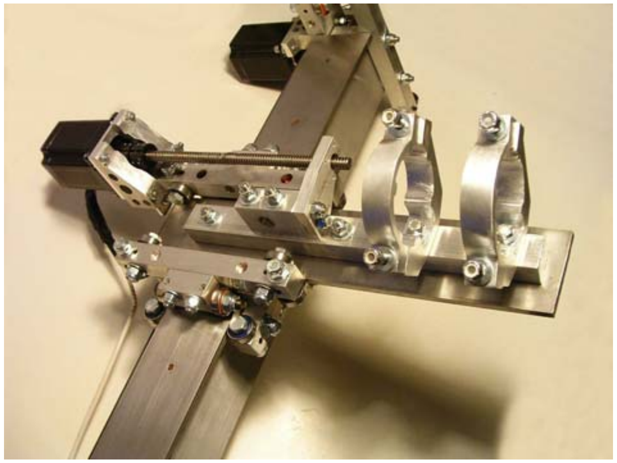
Gather the cable plate (part #19) and its stud. Install the stud with a nut and washer above and below the plate as shown.



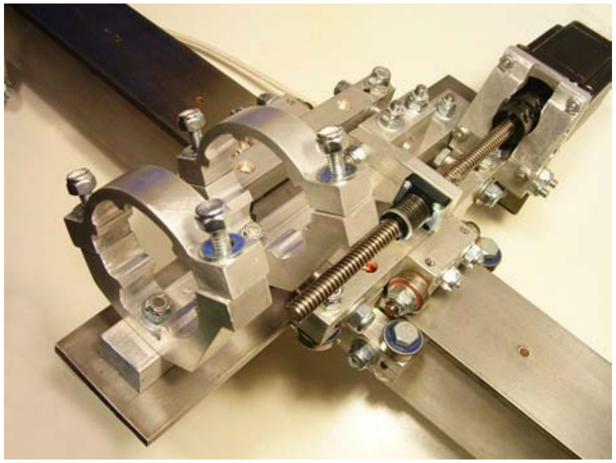
Install the motor to the Z axis motor mounts as shown. The cable plate is sandwiched between the motor and the mounts.
Use #10-32 x 1" screws at the front, and #10-32 x 2" at the rear. Use socket head cap screws if you can find them in this long length, otherwise substitute standard slotted head machine screws. Tighten the nuts fully. As these nuts are very vulnerable to vibrating loose, make sure to use lock nuts, lock washers, or threadlocking compound (not the permanent type).



Slide the Z axis assembly up into the bearings of the carriage. The Z axis drive screw should align through the center of the nut plate.



Slide the Z axis rail assembly into the carriage until the nut plate is about half way up the drive screw. Install the anti-backlash nut as shown in the photo to the right. Insert four #4-40 x 1" machine screws through the holes of the anti-backlash nut. The holes should align with the holes in the nut plate. If things are not aligning, loosen the nuts that attach the nut plate to the nut plate block and try to reposition it so that they do. If they will not, determine which holes may need to be filed out to allow more adjustability.
Install lockwashers and nuts on the screws holding the anti-backlash nut and tighten them to just snug.



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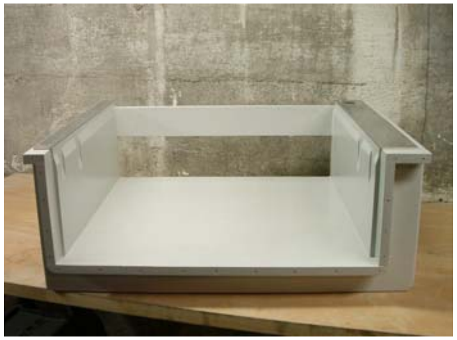
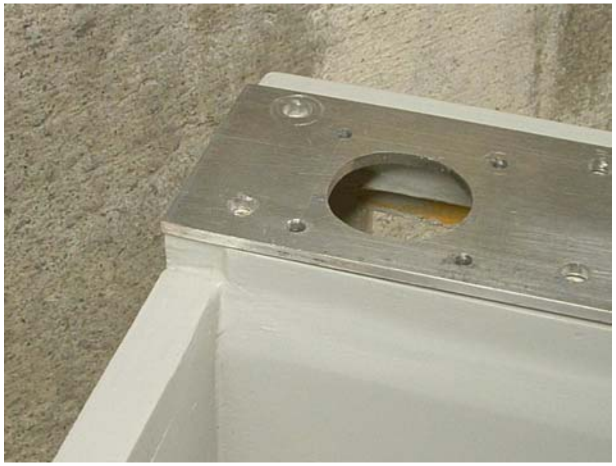
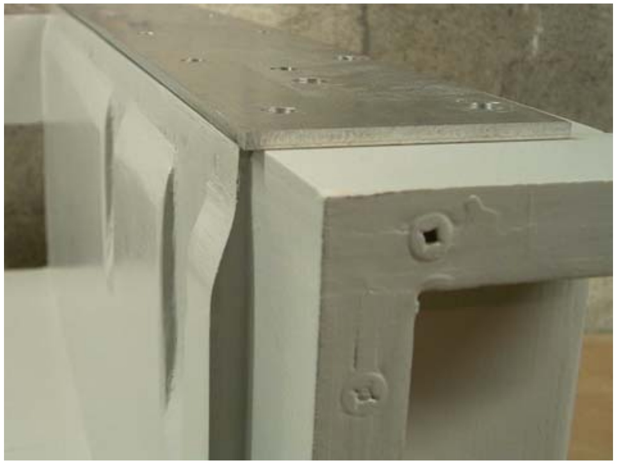
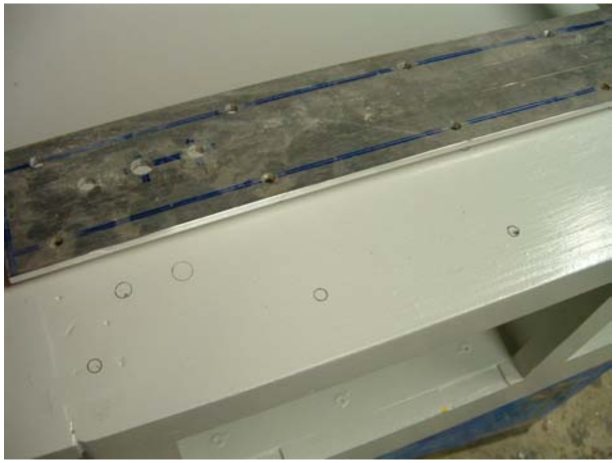


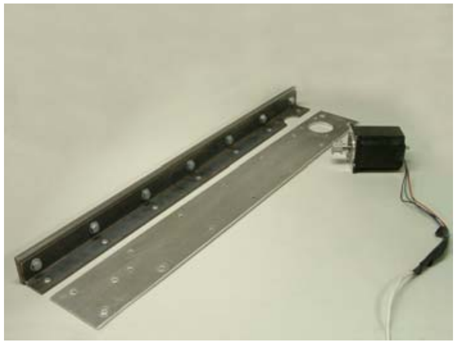
Set X motor plate(part #37) and X plate (#38) into position on completed wood machine base.   Note the photos to the right, which show their correct positions. The rear of the plates should be flush with the rear of the machine base. The long inside edges should be lined up flush with the rabbet that was routed out of the tops of the inner skins (middle right photo). Note that the front edges of the plates do not line up exactly with anything.





Carefully mark the locations of the holes using a sharp pencil. Remove the plates and drill 3/32" pilot hole down through the center of each marked location.

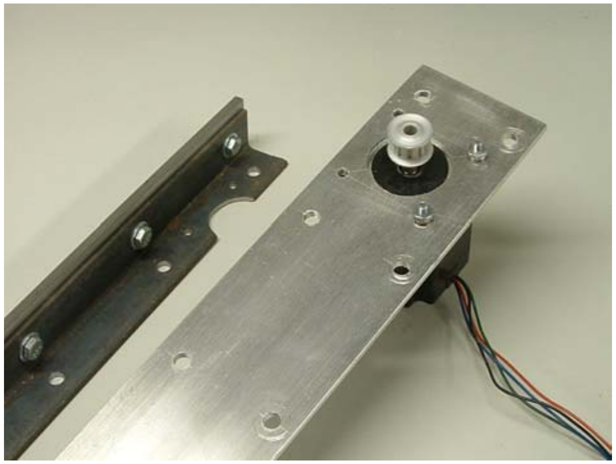




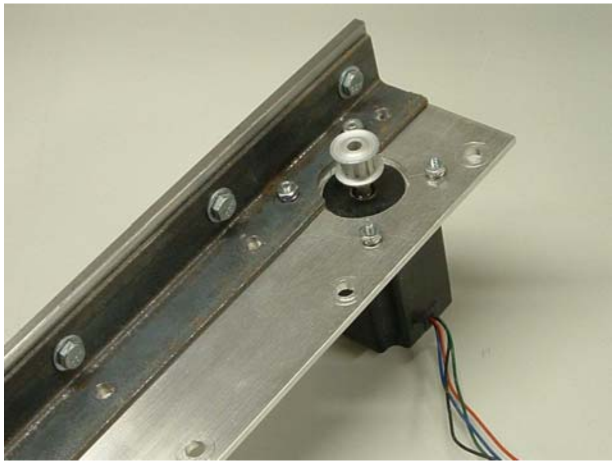
Using seven of the shortened 1/4-20 bolts, attach part #34 (X rail angle right) to part #33 (X rail right). The bottom face of the angle should be exactly flush with the bottom edge of the rail.

Gather this subassembly, along with the X motor plate (part #37) and a stepper motor.

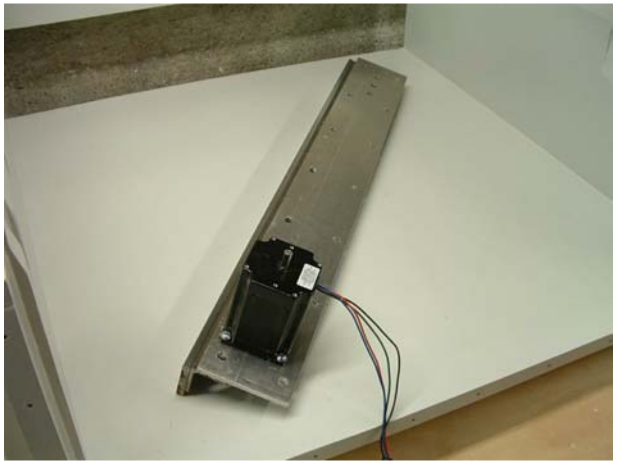
Attach the stepper motor to the motor plate with two #10-32 x 1" machine screws and nuts as shown to the right. Note that once the machine is assembled, these fasteners are very difficult to access. Due to this, it is highly recommended to use either locknuts or threadlocking compound (do not use the permanent compound that was used during the installation of studs).



Set the subassembly of the rail and rail angle onto the motor plate as shown at the right. Align the holes at the stepper motor and install the other two machine screws and nuts. Tighten them just snug at this point.

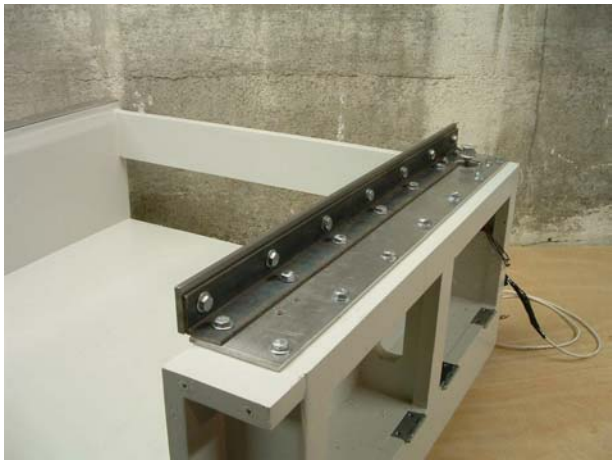


Flip the assembly over and make sure that the edge of the motor plate is exactly parallel to the X rail and X rail angle. Adjust its position if necessary and fully tighten the two motor screws that sandwich everything together. Make sure the other two are tight as well.



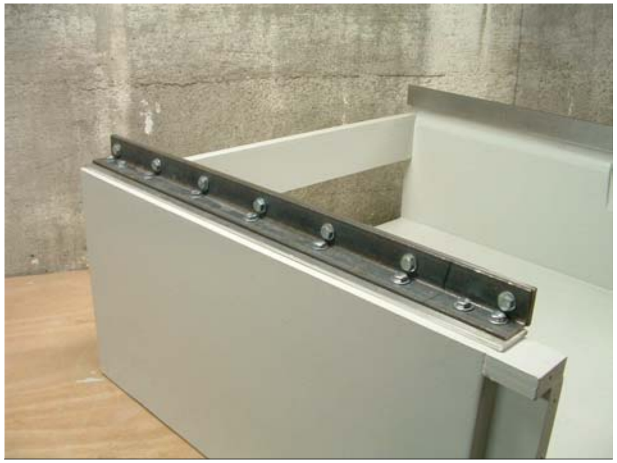
Set the motor plate/rail assembly into position on top of the machine base. Make sure the stepper motor wires are fed down through the machine.

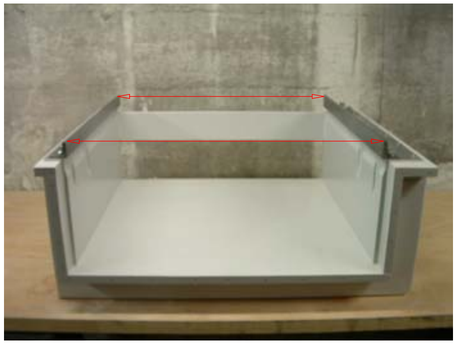
Realign the motor plate into the correct position, using the hole markings as a guide. Make sure everything aligns correctly as seen in the photos. When alignment is correct, thread the 1/4" lag bolts, with a washer beneath each head, into the pilot holes. Gradually tighten down the lag bolts, continually checking that the motor plate has not shifted its position.



The installed assembly should look like the photo to the right.

Using the other seven shortened 1/4-20 bolts, attach the X rail left (part #31) to the X rail angle left (part #32). Set this into position on top of the base. Use the same procedure of marking the holes, drilling pilot holes, and installing with the lag bolts.





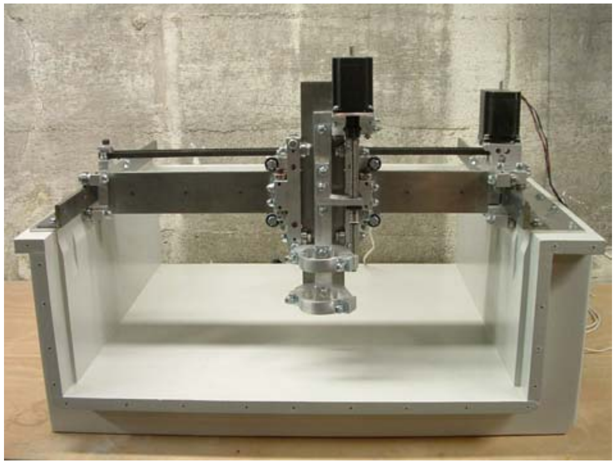
Measure between the rails at the points shown in the photo to the left. The rails need to be as parallel as possible, so if the measurements do not match, loosen the lag bolts slightly and adjust the positioning. If everything has been constructed exactly accurately, this dimension should be 24 3/16". If it cannot be adjusted exactly to this dimension, that is ok. It is most important that the rails be adjusted so that they are parallel.

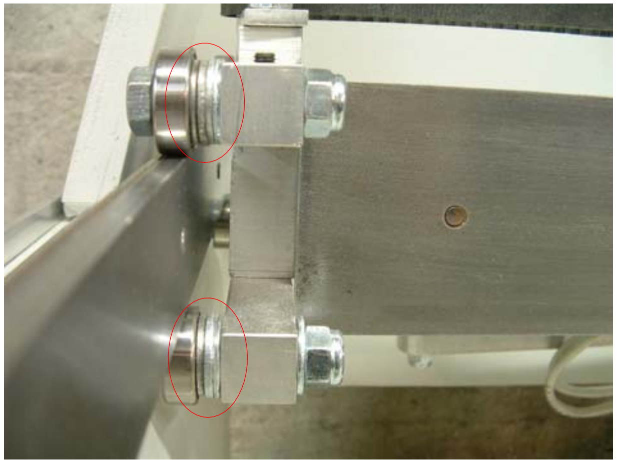
Once they are parallel, attempt sliding the gantry assembly onto the rails, as seen in the photo to the right. Go slowly and cautiously with this. There are a couple of potential problems that could occur due to inaccuracy in construction. The bearings may not be able to spread wide enough apart to fit onto the rails. The machine base may be slightly too wide, and the left side bearings may not reach onto the left rail. Or the base may be too narrow, in which case the gantry will not fit between the rails.

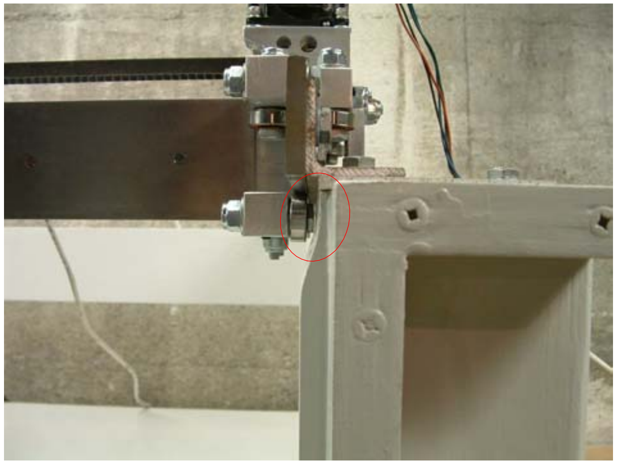
The bearing issue can be corrected by removing them and hand filing out the holes slightly to get more adjustment range. If the gantry is too short relative to the distance bewteen the rails, the left bearings can be spaced to the left with the addition of washers. If the gantry is too long relative to the distance between the rails, this may require the most invasive corrections. If the rails cannot be positioned wide enough apart, the gantry assembly may need to be taken apart far enough that the gantry tube itself can be shortened. This would also require elongating the slots in the left end of the gantry tube, and potentially shortening of the Y drive belt.

My own build had the second problem, which I was able to correct by simply adding washers, as seen in the middle photo to the right.

Once it looks like the gantry will slide on smoothly, be extrememly cautious in moving it onto the rails. There is very tight clearance between the heads of the lower bolts and the inner skins of the machine base (red circle in the photo to the right). The gantry must be kept as perpendicular as possible to the rails, keeping pressure to the left, to avoid having the heads of these bolts gouge the skin surface.







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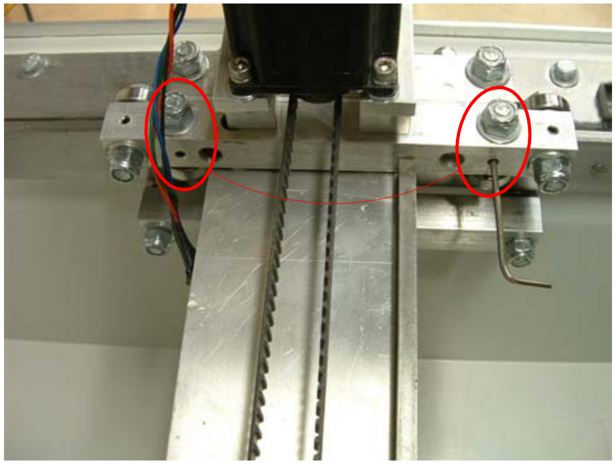
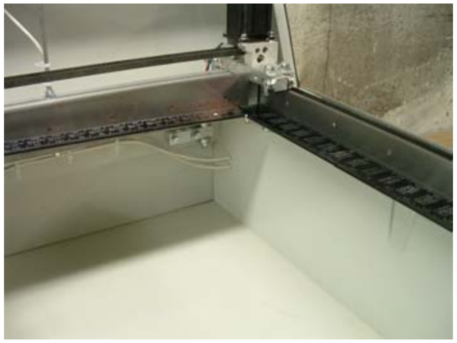
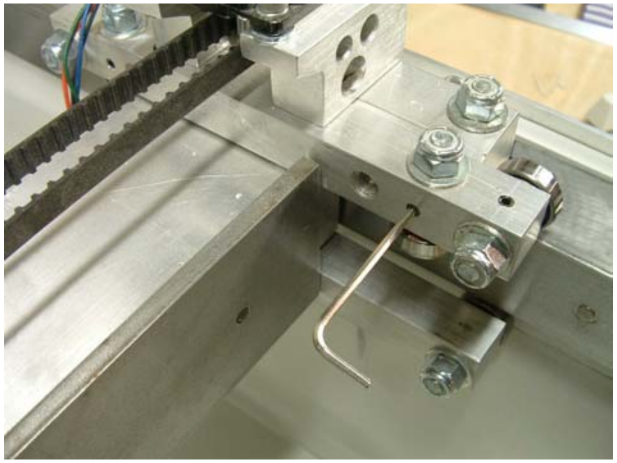
For now, we will make just one initial adjustment to the machine. That will be to the four bearings that contact the top sides of the right X rail. Adjusting these will correctly will prevent the lower bearing bolts from gouging into the skins (bottom right photo on previous page) and will also set the gantry at a right angle to the X axis.



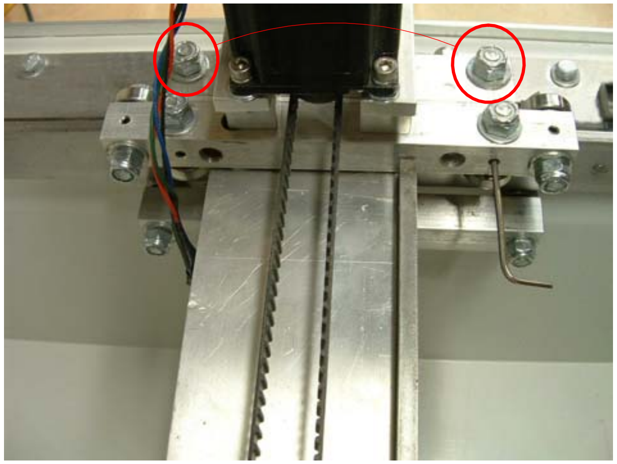
Begin by working with the two bearings that are circled in the photo to the right. Apply pressure on the gantry, and gently push it to the right of the machine, so that the two bearings are both touching the X rail. Tighten the bolts/nuts on the bearings just slightly snug, so that the bearing cannot rock back and forth, but tightening the set screw will still move it sideways.





Turn the set screws in until the heads of both of the lower bearing bolts (last photo on previous page) have about 1/16" or more clearance. Next, with the gantry pushed all the way to the rear, set a framing square between the X and Y rails as shown in the photo to the left. Now continue to adjust the two bearings so that the rails are exactly perpendicular.

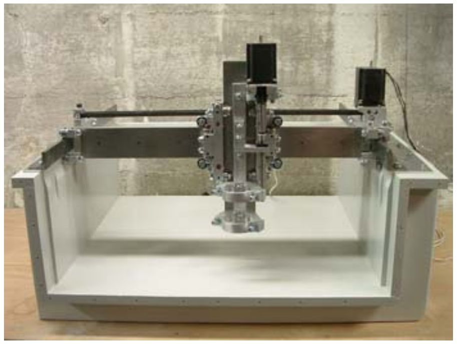
This adjustment is attempting to satisfy two conditions at once, so it may take some trial and error, and a little patience.



When happy with the lower bolt head clearance and that the gantry is perpendicular, adjust the other two bearings (circled in the photo to the right) so that they are in light contact with the X rail.

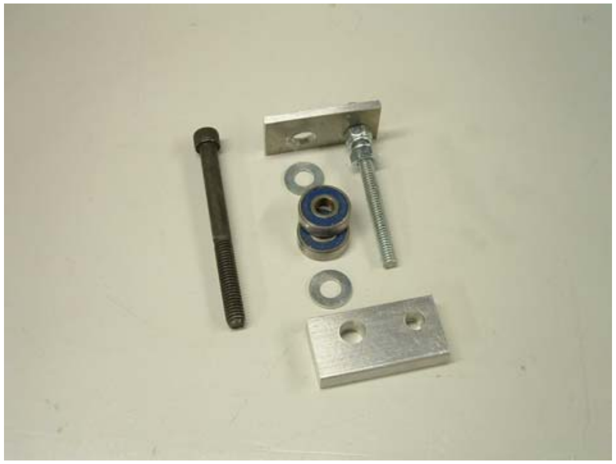
For further details on general alignment procedure, take a look at page 134.

With these 4 bearings adjusted, the gantry should be able to move forward and back without binding or hitting anything. It is does, stop and investigate. You may need to do so other temporary corrective adjusting at this point.

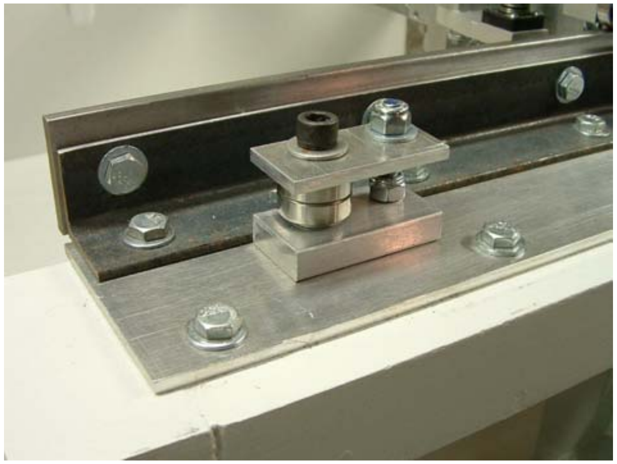


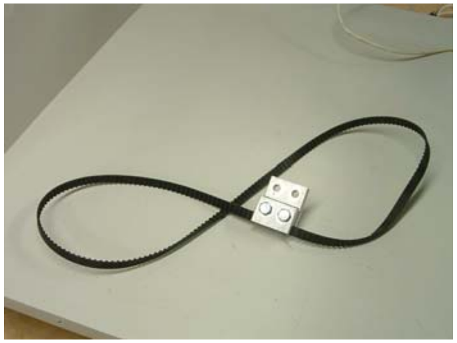
At this point the machine should look like the photo to the left.

Gather the parts for the X belt idler pulley as seen in the right photo (parts #35 and 36, stud SH, 3" socket head cap screw, bearings and washers.)

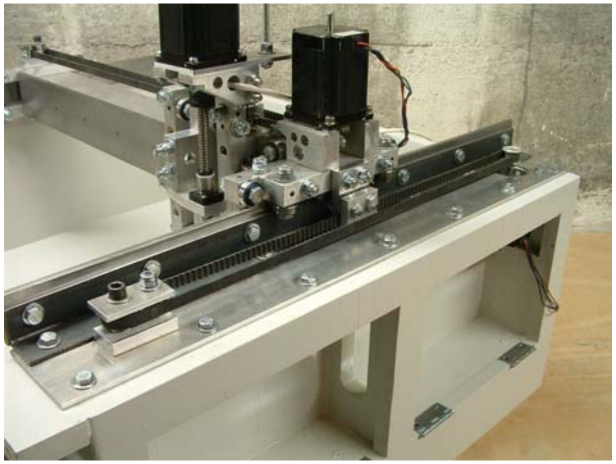


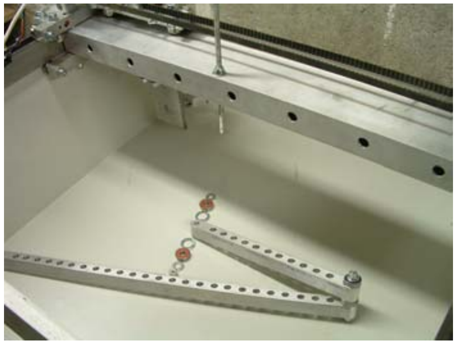
Using the exploded view drawing on page 31 as a guide, assemble the idler pulley.





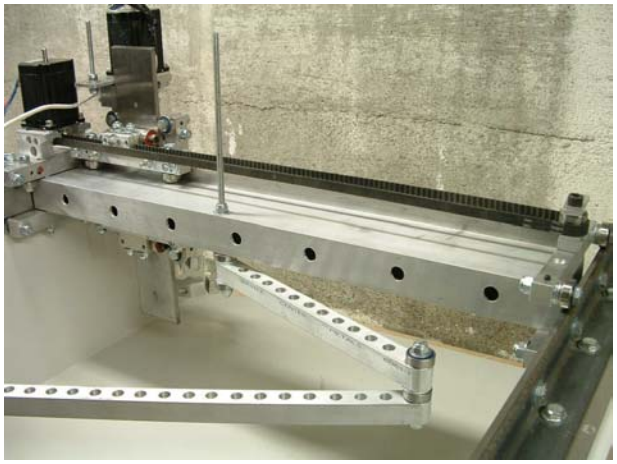
Use the same general procedure that was used on the Y belt (page 111), to find the length of the X belt. Cut it to length. It may be easiest to install it by removing the belt clamp pieces and clamping it into these first, using two 1/4-20 x 1" bolts and locknuts. Then temporarily remove the idler pulley and install the belt. Replace the idler and pull it so that the belt is tight. Tighten it in place.

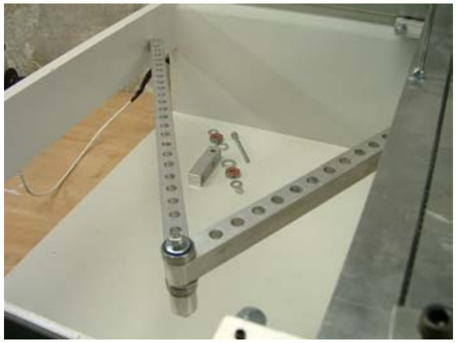




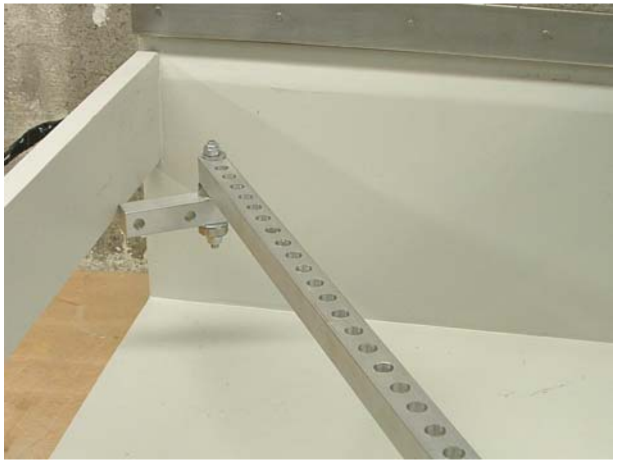
The cable arms provide a way of organizing all of the wiring that needs to reach out to the gantry. Commercially available cable track, which rolls along an axis as it moves, may obviously be used instead, but this is an inexpensive alternative way of managing the wiring.

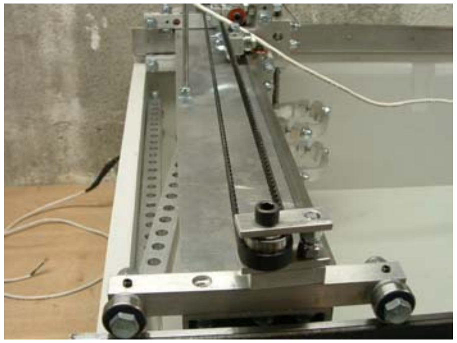
Using the exploded view drawing on page 32 as a guide, assemble cable arm 1 (part #39) to cable arm 2 (part #40). Tighten the nuts on the stud so that they are just tight enough to remove slack and that the washers will not slide sideways, but not tight enough that the assembly takes force to open and close. These bearings are not designed to have side loads placed on them, so be cautious in overtighening.





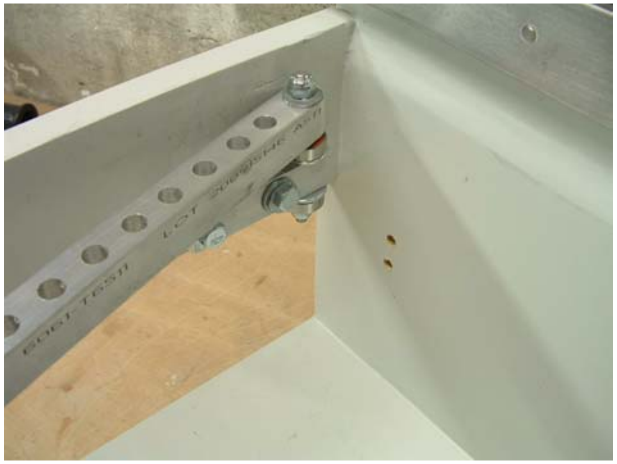
Install stud SJ down through the hole in the gantry and assemble the cable arm assembly to the bottom of it (top right photo). Assemble the cable arm mounting block (part #41) to the rear of the cable arm assembly as seen in the photos to the left and right.

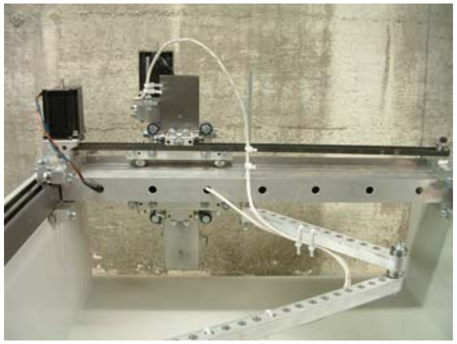




Push the gantry all the way to the rear, as seen in the photo to the left. With it in this position, look beneath the gantry, making sure the cable arm assembly is horizontal, and mark the location of the mounting block on the rear plate. Pull the gantry forward so you have room to work and lag bolt the mounting block into the marked position.

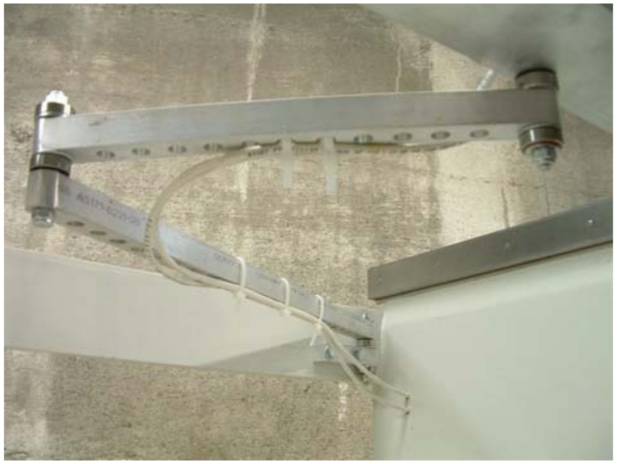
Move the gantry forward and back. The cable arm assembly should move smoothly, without binding or adding any noticable force to that which is required to move the gantry.



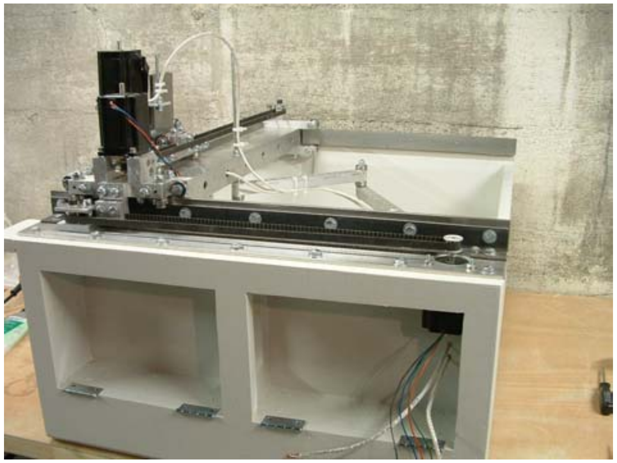


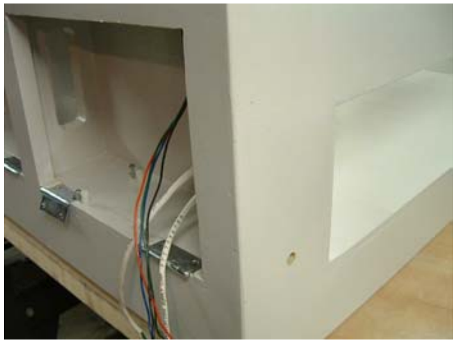
Route the wiring for the Y and Z stepper motors as shown in the photos. Simple cable ties are used to secure them to the cable arms. Be sure that there is no way that the cables can hook anything or bind as the gantry and carriage move through their full range of motions. Also be sure that the wiring being used is intended for applications where it can be repeatedly flexed. A wire that breaks while the machine is under power can cause many stepper drive boards to be destroyed.

Note that I drilled two holes in the right skin for the cables to enter the electronics area.



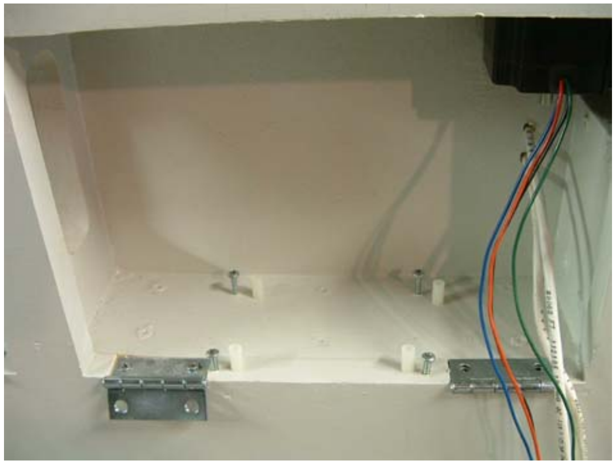
Make sure you have provided enough cable length on all 3 stepper motors to adequately reach the location of the drive board, without being pulled taut.



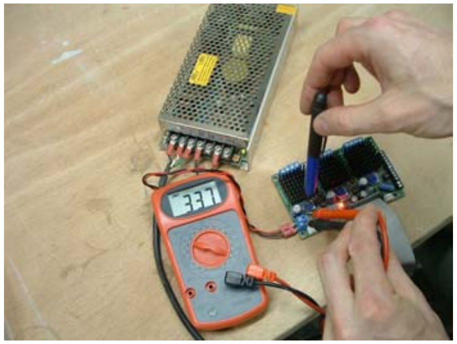


Drill a hole through the rear plate for the power supply cord to enter the machine, as seen in the photo to the left.

In the right photo, I have marked the location where the drive board will be mounted, and am pre-installing the screws. It will be mounted on the four small nylon standoffs that are next to the screws. To avoid overtightening the screws that hold the drive board in position, I used an awl to create a pilot hole, and then threaded the screws into place without the board. I used the standoffs to make sure the screws were at least as deep into the wood as they would be with the board in place. Now when installing the board, the screws will go into their holes easily, allowing a more careful feel for when they start to put pressure against the fragile circuit board. This also prevents having to put a lot of pressure on the screwdriver, which could cause it to slip off and damage the board.



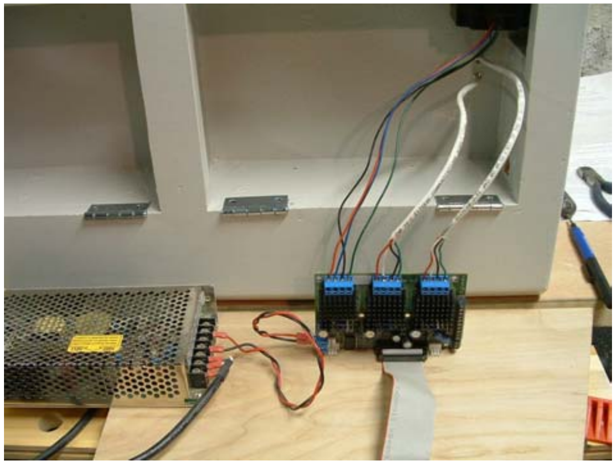
version 1.2



A full description of electronics installation is beyond the scope of this manual, and you should always fully follow the manufacturers instructions. However, I will briefly run through the installation of a Xylotex board. Again, this is not intended as a complete set of installation instructions- follow the manufacturers instructions to the letter.

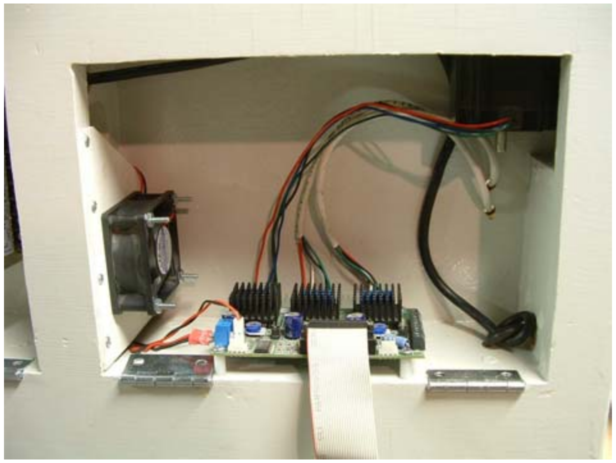
The Xylotex requires setting the output voltage for each axis. This is done with only the power supply hooked up, and using a digital multimeter (left photo). A small potentiometer is turned to achieve the desired output voltage.

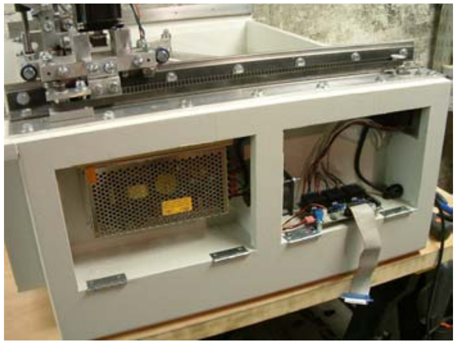
With the "Vref" voltages set, the board can be wired to the motors (right photo).



In the photo to the right, the drive board is mounted and wired. The power cord for the power supply enters from the right, and is routed up over the board and into to the left side of the space. Notice it is knotted to prevent it from being pulled through the hole.

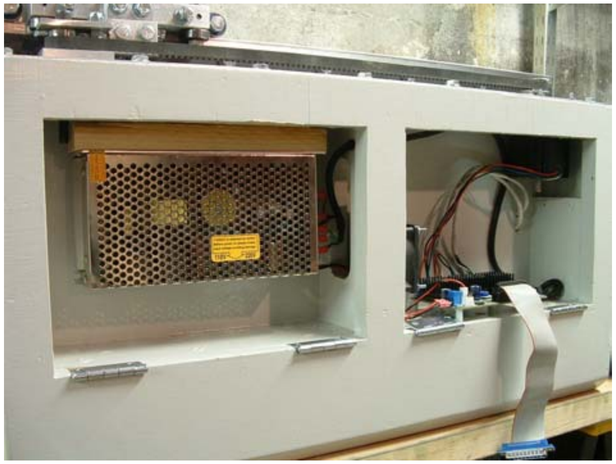
When using this board at its higher voltage outputs, a cooling fan is required. I mounted a small fan, which is powered by the drive board itself, to a small piece of mat board. I cut a large diamter hole in its center, and smaller holes for the mounting bolts. I simply screwed this in a position where it will blow air over the heat sinks on the board.



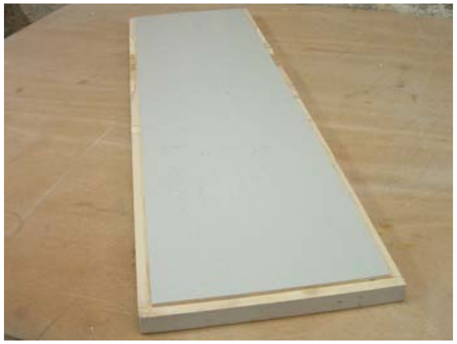


I cut a couple of small pieces of wood blocking and attached them to the top surface of the left side of the space. I attached the power supply to this. It is essentially "hanging" from the top. This put it in a convenient orientation to run all of the wiring.

Plan your layout carefully so that wiring is neat and is easily traceable. More wiring will be added later for an emergency stop button and axis limit switches, so plan for this wiring as well.

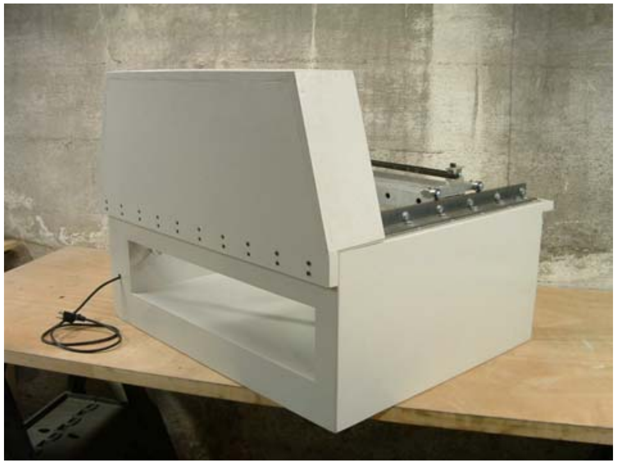


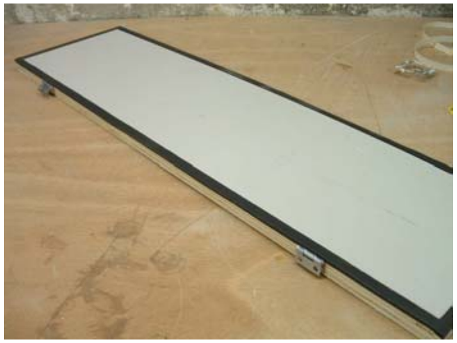
version 1.2



The machine is equipped with a rear door. This allows stock that is longer than the machine bed to pass through, giving a larger effective work area.

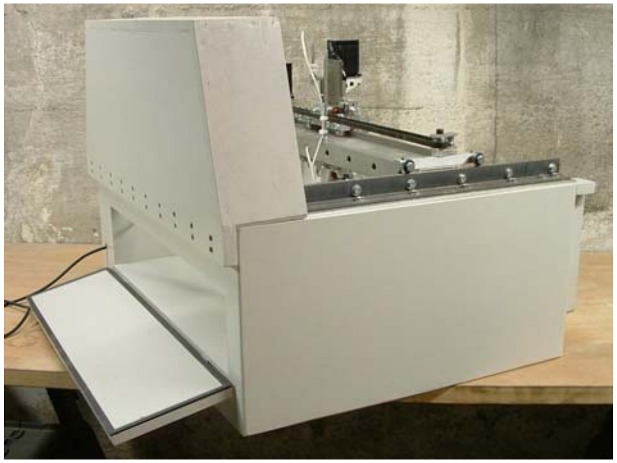
Use the router to cut a rabbet around the perimeter of the inside face of the door. (photo to the left) This notch will be filled with foam self-adhesive weatherstripping to seal the door against both dust and sound transfer.
Rout it to the width of the foam weatherstripping and to a depth that is about 1/16" less than the thickness of the weatherstripping. This will cause the faom to be in compression when the door is closed, providing a tight seal.





Install the weatherstripping into the groove as seen in the photo to the left.

Install the door with two 2" utility hinges, or one continuous piano hinge.



Install the door so that there is about 1/16" gap between the top of it and the bottom of the rear cover flange.

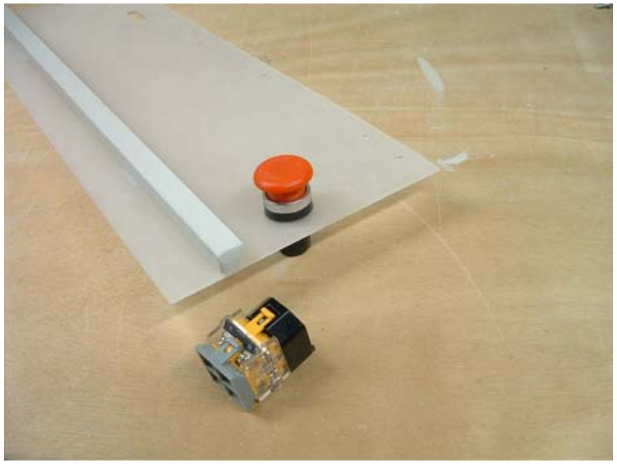
I didn't anticipate using this feature often so I simply held the door closed by drilling two holes through it and installing screws. This provides the tightest seal, but requires removing the screws to open the door. Install latches if you anticpate using the door often.

version 1.2

The side door that covers the electronics area is made of polycarbonate, which can be drilled easily for mounting hardware and the emergency stop button. I sanded both sides of the polycarbonate with 220 grit sandpaper on a random orbital sander to give it a frosted appearance.

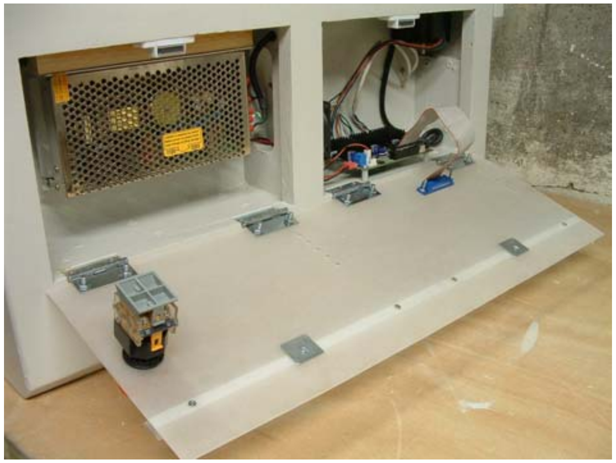
I ripped a small strip of wood the length of the door to act as a handle and as a stiffening strip.

A hole can be cut into the door to mount the emergency stop button. This is a large diameter hole and can be cut by drilling a series of closely spaced holes and then filing it out to the the final diameter. This is the same technique that was used to cut the thick aluminum plate.

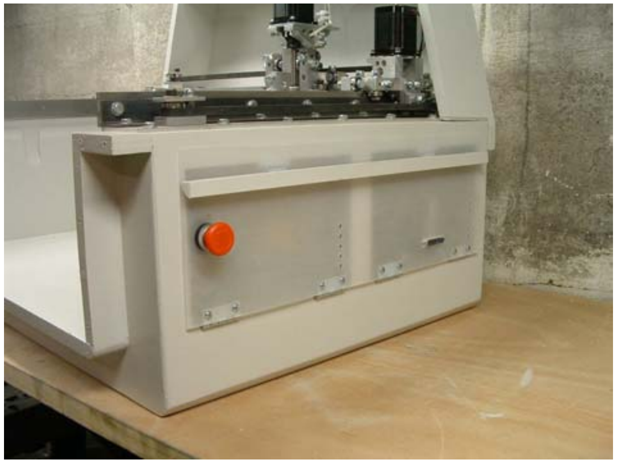


Mount four 1 1/2" utility hinges at the bottom edge of the door. Magnetic, or friction fit, latches can be used at the top edge to keep it closed. In the photo to the right, the catch plates are screwed through the door plastic and into the wood handle strip. A few additional screws have also been added along the length of the handle.

A hole was also cut to mount the parallel port cable right to the door. This provides a convenient location to plug the computer in.

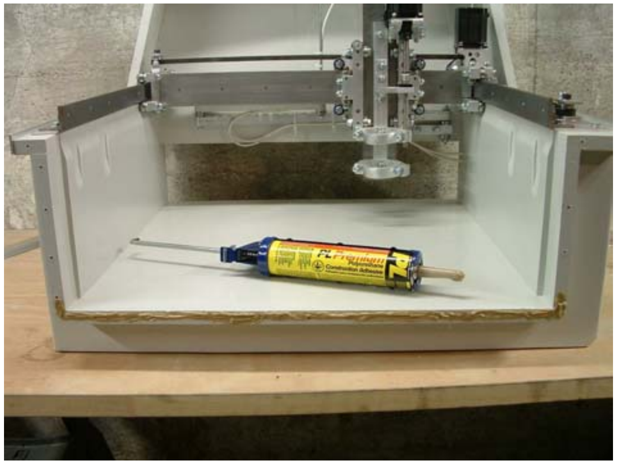


Strips of ventilation holes were added, for input air at the rear side of the fan, and exhaust beyond the drive board.



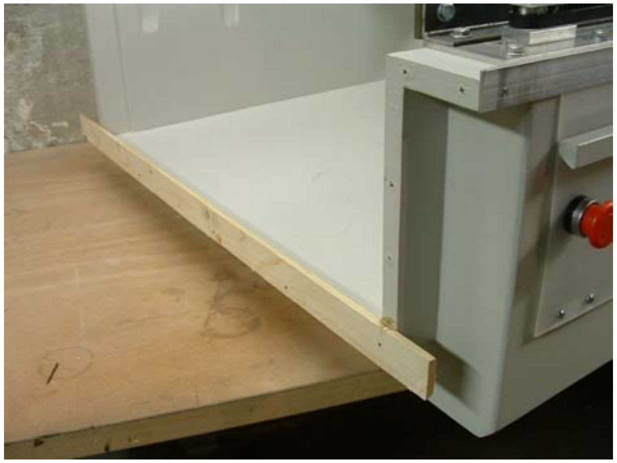
To acheive a high level of accuracy in the machine's alignment, a thin layer of epoxy resin will be poured on the bed area to level it. An epoxy with a very low viscosity will self-level and potentially result in a surface that is very flat. This surface can then be used as a reference plane, from which all of the machine's alignment measurements are taken.

To pour the epoxy, we need to create a watertight dam to contain it to the bed area. This can be done by adhering two strips of wood to the front and back of the machine as shown in the photos to the right. I used a construction adhesive, but a sealant such as silicone, or latex caulk could also be used. What is most important is that the area will have no leaks. The epoxy is very thin and will run out of the smallest crack or area of porosity.



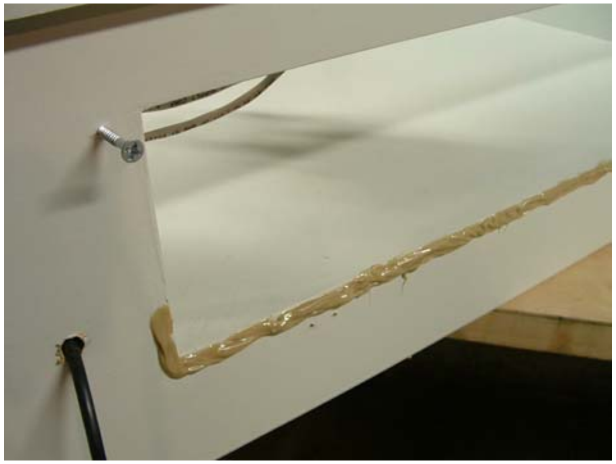
After applying the adhesive or sealant, set the strip of wood into it and move it side to side to make sure there is a continuous application. Attach the strip with a few finish nails. As the adhesive compresses out of the joint, run your finger along the inside edge of the joint to smooth it out and further ensure a continuous seal.

Make sure the joint between the bed of the machine and the vertical skin panels is watertight. I had applied enough layers of paint that this was the case, but if in doubt run a very small bead of sealant along this area as well.



Attaching the rear dam strip required temporarily removing the rear door.

Once the bed area is sufficiently dammed, the machine must be set as level as possible (left photos). Place it on a surface that cannot move during the duration of the time the epoxy requires to cure (at least 24 hours). Make sure the surface cannot wobble or move at all. Next, use a level to get the bed of the machine as level as you possibly can. Place shims under the corners of the machine as required to bring it level. Note that I am using a length of aluminum tubing (the one I use for a guide fence with my circular saw) under the level to raise it up above the dam strips that I installed.

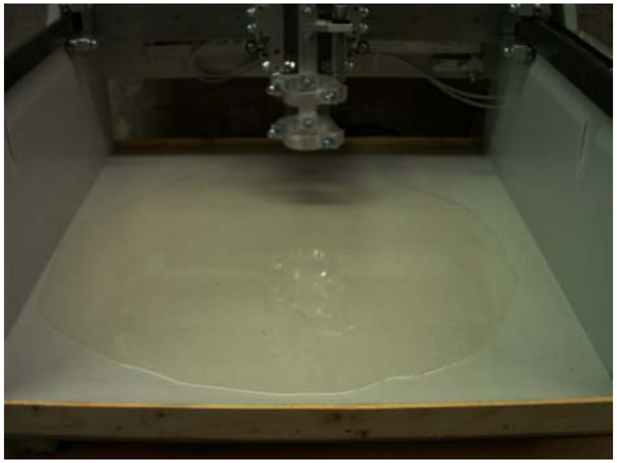


version 1.2

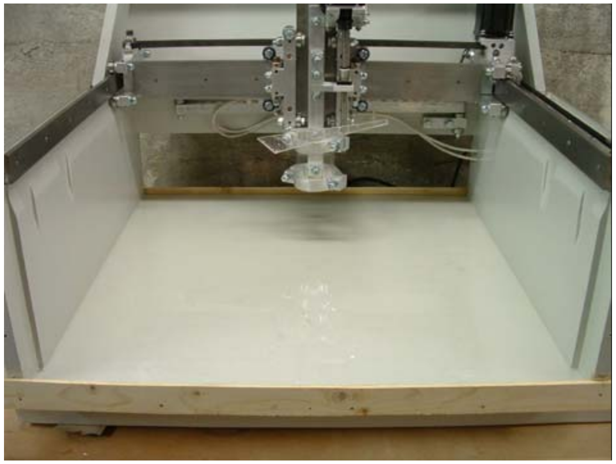
Use an epoxy with as low a viscosity as possible. The brand I used advertises a viscosity of about 550 cps, which is quite thin. Note that the warmer the epoxy is, the thinner it will be. However, if it is warmed too much, it will cause it to harden too fast. An ideal compromise is to get the epoxy to about 80 degrees fahrenheit.

I mixed a total of 32 fluid ounces of epoxy (one quart). This should result in an average epoxy thickness of a little under 1/8". The more inaccurately the wood base was constructed, the more epoxy it will take to arrive at a perfectly level coating of epoxy. The 32 ounces is probably about the minimum that can be used to lay out perfectly flat. I used the slowest hardener available for the resin to allow it as much time as possible to settle out to a flat condition.

Although a high quality epoxy will have few solvents and will produce very little odor, make sure you have adequate ventilation in your work area. Set up an exhaust fan if possible. Double check that the machine bed is as level as possible and mix the epoxy. Use a graduated cup for accuracy and follow the manufacturers mixing directions.



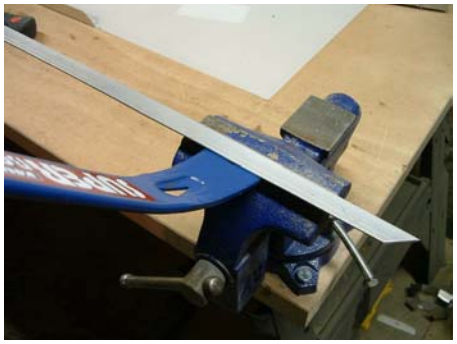
Pour the epoxy into the center of the machine bed. As seen in the photo to the right, it should immediately run out to cover most of the bed. It will probably require some spreading to overcome the surface tension that will prevent it from completely covering the base on its own.



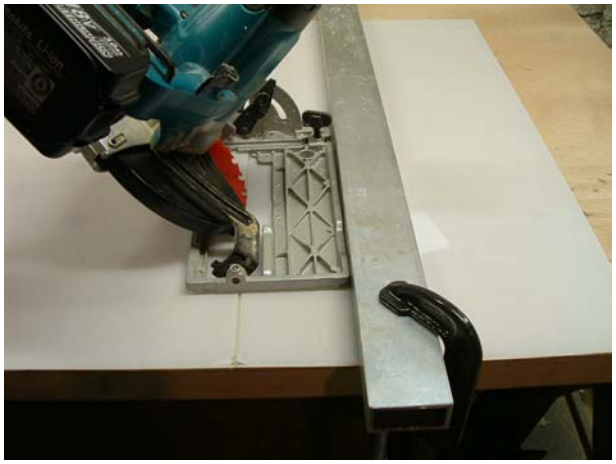
I used a piece of polycarbonate plastic that was left over from fabrication of the cover parts as a spreader. It can be seen resting on the router mounts in the photo to the right. Carefully spread the epoxy out into the corners. Be cautious both when mixing the epoxy as well as spreading it that you do not introduce excessive air bubbles. Trapped air bubbles will stand proud of the flat plane of epoxy when dried.

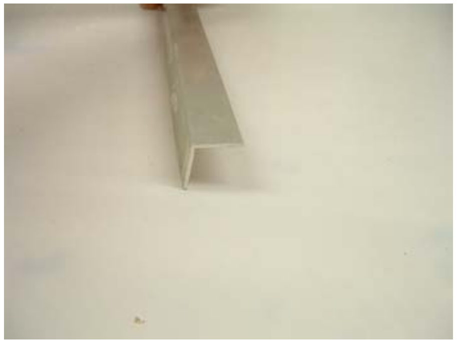
Once it is covering all of the surface area, it should self-level to a flat plane on its own. Now leave the area and don't touch anything until it is completely cured. Some epoxies can be heat cured at a temperature of around 120 degrees to provide a stronger, more durable surface. Follow manufacturers directions.

version 1.2



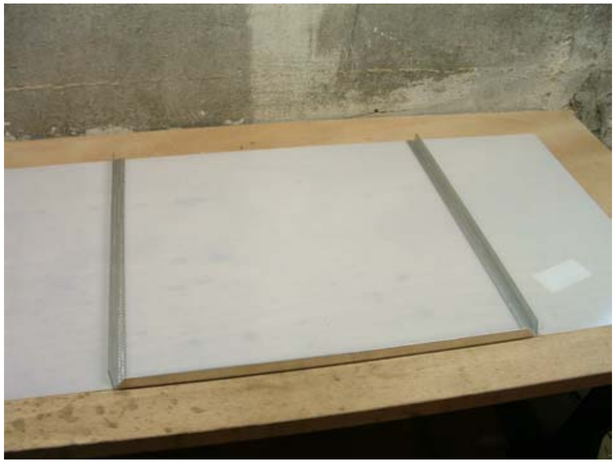
Following the exploded view drawing on page 35, the assembly of the plastic cover is relatively straightforward. The plastic pieces are joined with 1/16" x 3/4" aluminum angle (not illustrated in the drawing on page 35). These strips sit to the inside of the plastic. As the sides of the cover and the top are not at 90 degree angles to each other, the two lengths of aluminum angle that join them must be altered slightly. This can be accomplished by holding it in a vise and carefully using a flat pry bar to open up the angle (photo to the left). Gradually work along the length of the piece until is is consistent. Be careful not to pry it too much at once or it may kink or become wavy. You should end up with pieces that look like the middle left photo.

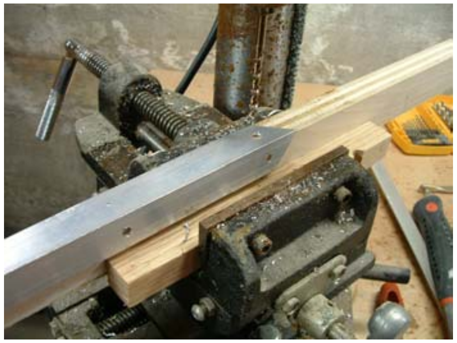




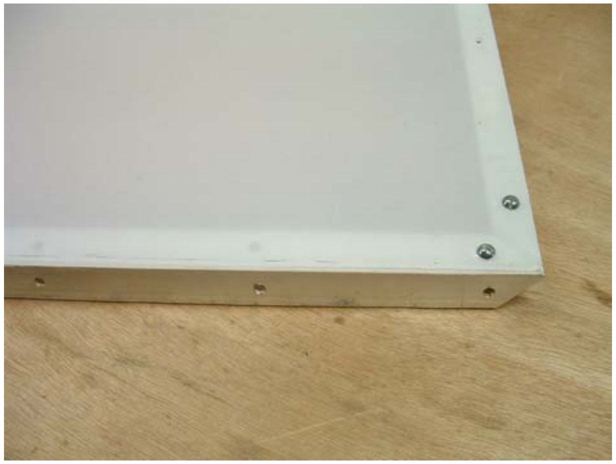
The polycarbonate sheet can be cut with a circular saw. Use a clamped fence to achieve a straight cut. I angled the saw 45 degrees to put a miter on the edges, but this is not necessary. Set the blade depth to just penetrate through the material. Leave the protective covering on the polycarbonate as long as possible, as it scratches relatively easily. That is why the plastic looks white in these photos, it still has its protective film on it.

To measure the lengths needed for the aluminum angle, you can use the finished plastic parts to mark from. Cut the aluminum with 45 degree mitered corners, so that they will all fit together without overlapping.



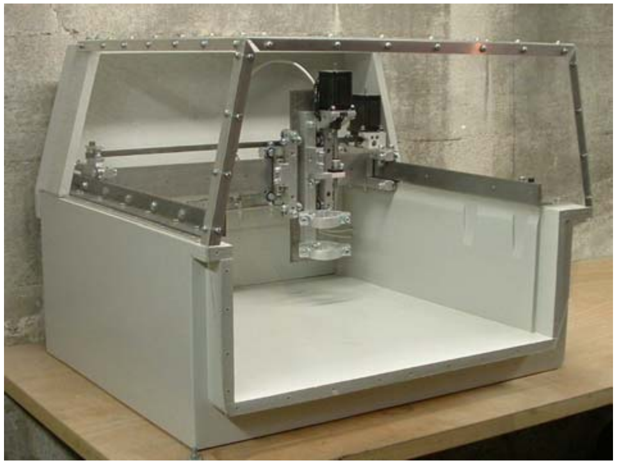


Drill evenly spaced (about 4" apart) 3/16" holes to allow bolting to the plastic. Transfer the hole locations to the plastic with a marker. To keep things accurate, mark and drill the two outermost holes into the plastic, and assemble the plastic to the aluminum with 1/2" long #8 machine screws. Now the parts will not shift as you mark the remaining holes onto the plastic. Separate the parts and drill the plastic. When all of the holes have been drilled, remove the protective covering on the the plastic and assemble the cover with #8 machine screws. Use lockwashers.

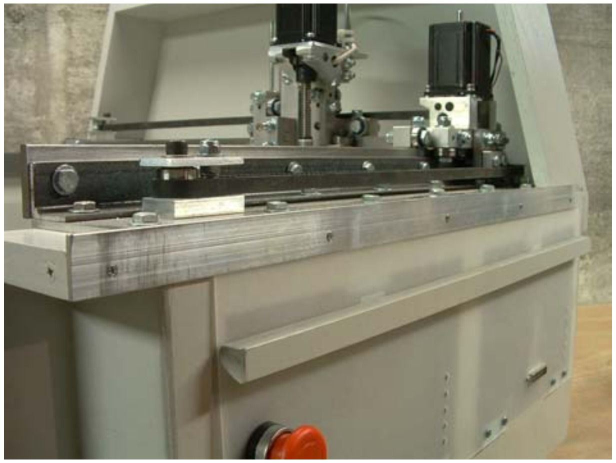


version 1.2

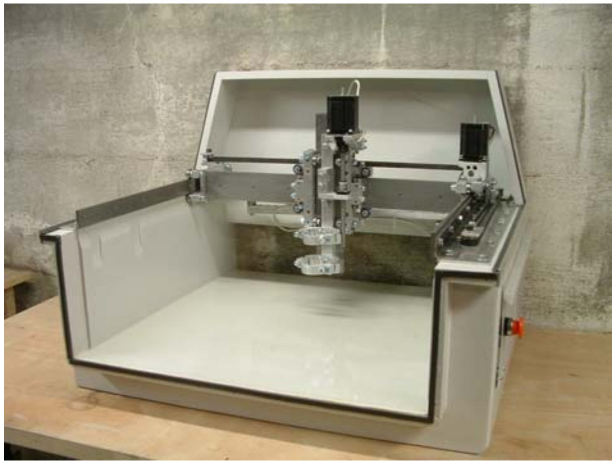
The assembled plastic should look like the photo to the right. Set it in position on the machine to make sure it seems to fit correctly. There should be a couple of inches of overlap between the plastic and the wood flanges to which it will be attached with a hinge.



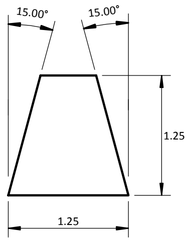
Cut another length of the aluminum angle to 26" in length. Drill 5 evenly spaced mounting holes (about 1/8" dia.) along its length, approximately 1/4" from the edge. Cut two lengths of 1" wide x 1/16" or 1/8" aluminum flat stock to 22 1/2" long each. Drill 5 mounting holes in these as well, about 3/8" from the edge. Mount the two strips to the sides of the machine, as shown in the photo to the right, with small wood screws. These hold the plastic cover from slipping off of the side.



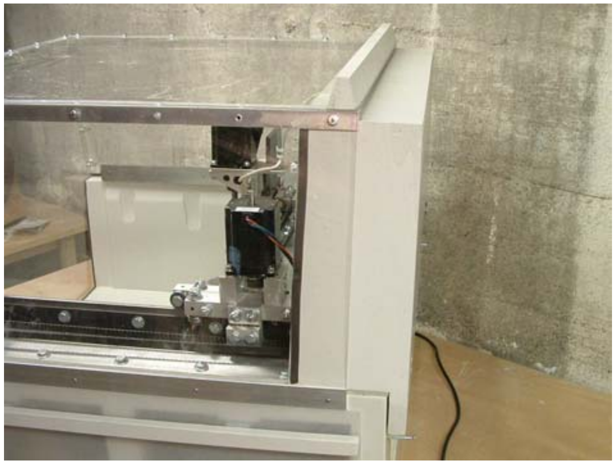
Optional: Apply a length of self-adhesive foam weather-stripping (left photo) along the surfaces where the plastic cover touches the base (right photo). This will help make it more dust tight and reduce vibration.

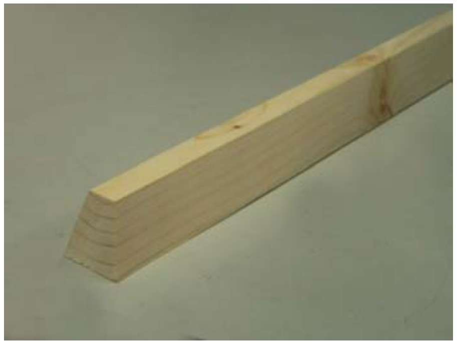


version 1.2



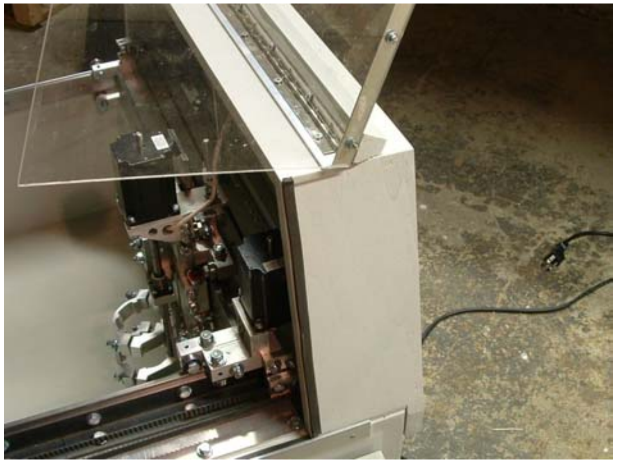
The plastic cover attaches to the wood flange with a continuous piano hinge. The hinge can either be attached to the plastic with the same #8 machine screws that were used to hold it to the aluminum angle, or a wood strip (dimensions at left) and wood screws can be used. The wood strip is sized so that it provides a rest for the cover when it is in its fully open position, as seen in the middle right photo.



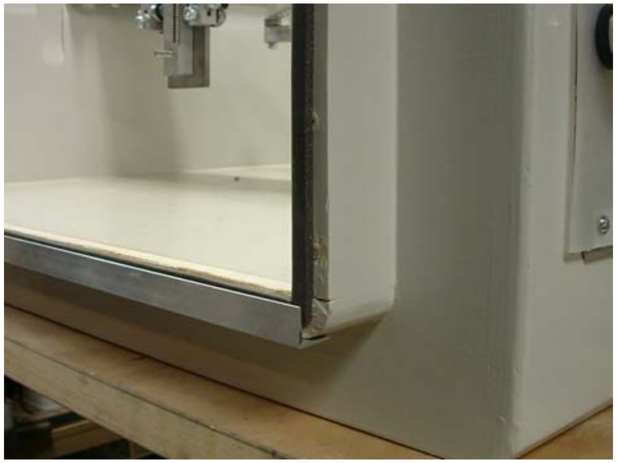


If using the wood strip, trim its length to match the width of the cover. The photo to the left shows its ends also trimmed at an angle to match that of the cover sides.

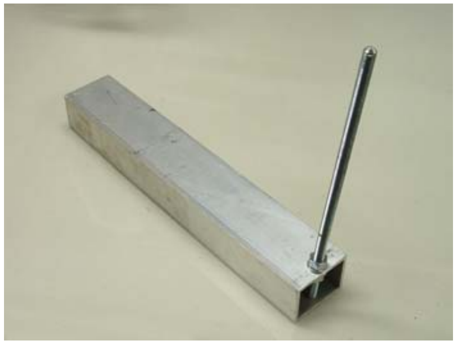
With the hinge attached to the plastic cover, set the cover in place and mark along the rear edge of the hinge to note its location. Hold the cover in the open position and attach the hinge to the flange with small wood screws.



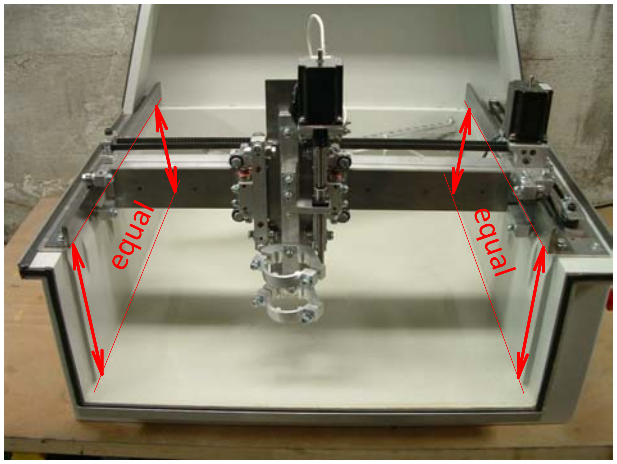
Attach the strip of aluminum angle to the lower front flange. This will hold the cover closed at the bottom edge. Make sure to leave enough clearance for the thickness of the cover material to slide behind it.



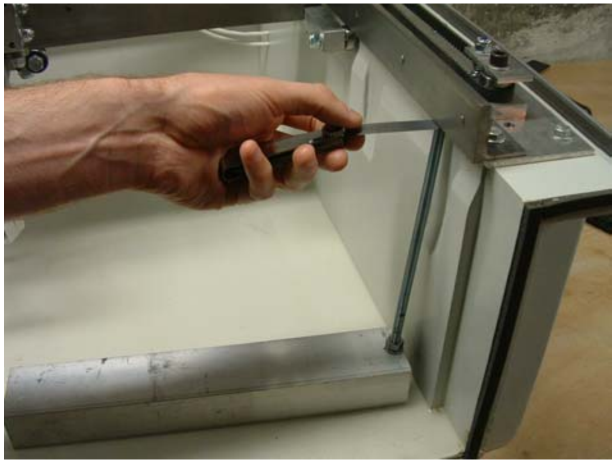
version 1.2



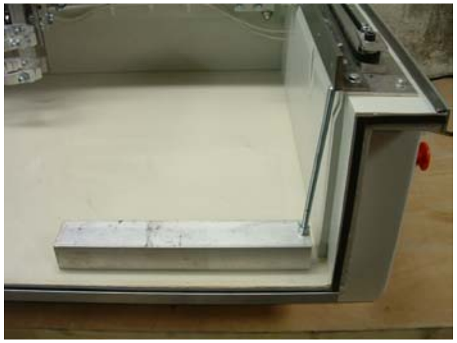
At this point the machine is basically finished and primarily needs alignment before using it. If you haven't already done so, this might be a good time to get the electronics fully operational as well as getting machine control software configured. If you can jog the machine position with the computer it can make alignment easier, especially in the Z axis.

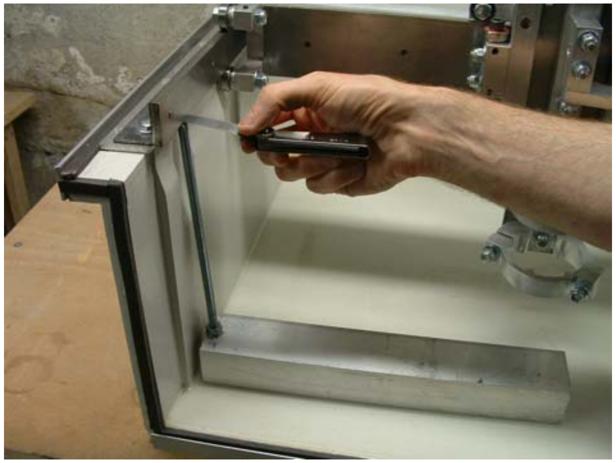


The first alignment step will be to get the two X rails exactly parallel to the surface of the machine bed. This is done by measuring up from the bed at the front and rear of each rail, and adjusting it so that the measurements are equal. This can be accomplished with some relatively simple tools. I constructed an adjustable height gauge from some scrap rectangular tubing and a length of threaded rod. The size I used was 1 1/2" x 2". The surfaces of the tubing are very flat and allow the gauge to sit against the bed without rocking. The top of the threaded rod was filed to a shallow point. Note in the lower left photo that I also bent the threaded rod very slightly to the side so that it would reach exactly under the rail.



The height gauge is used in conjunction with a set of feeler gauges (middle left photo). These are simply thin flexible metal strips that are inserted into a gap to "feel" how wide it is. They can be purchased at any auto parts store for a few dollars. Adjust the threaded rod up under the front of the right X rail until it is almost touching. Ideally, leave about .010" of clearance. Use the feeler gauges to measure this gap. With trial and error, find the feeler gauge strip, or combination of strips togther, that slides into the gap with just a faint amount of drag along its surface. Without changing its adjustment, reposition the height gauge under the rear of the right rail. Measure the gap between it and the rail with the feeler gauges. Loosen the bolts holding the rail to the rail angle and reposition it so that the gap is the same at the front and rear. This may take moving the height gauge from front to back several times and taking repeated measurements. With some patience you can get the rail very accurately positioned this way. Do the same for the left rail. Note that it is about 1/8" higher from the bed than the right rail, so the height gauge will need to be readjusted. The left and right rail heights are not equal to each other, they are simply equal along their own lengths, front to rear.

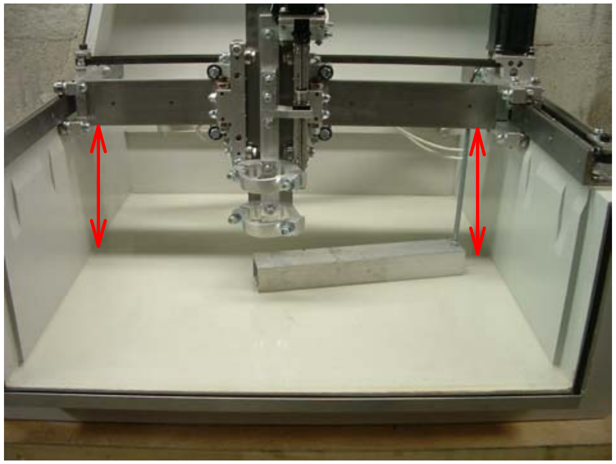




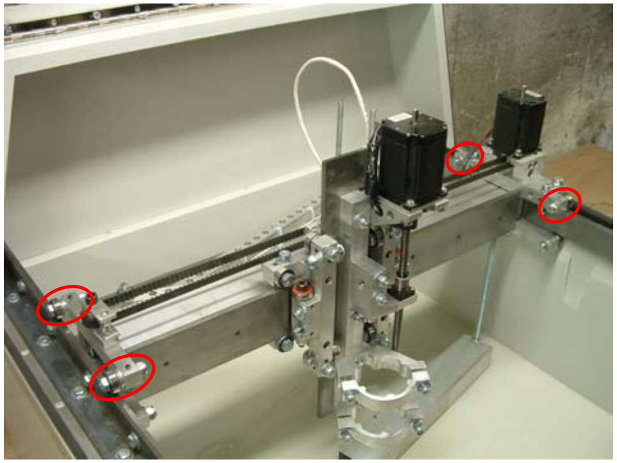
version 1.2

The two X rails should now both be parallel to the machine bed. The next adjustment is to get the Y rail parallel to the bed. This is done in a similar fashion, but we will now be adjusting bearings to affect its height.

We will again be using the height gauge and feeler gauges, this time to measure the left and right sides of the Y rail (right photo).

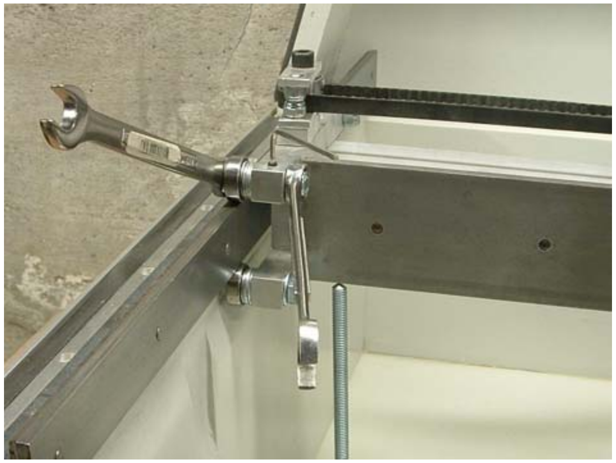


The four bearings that ride along the tops of the X rails will need to be adjusted (circled in the right photo). All four will need to be exerting equal pressure downward on the rails so that the gantry will not rock. Again, this will require some trial and error and multiple repositioning of the measuring gauge during the process. Tighten the nuts on the bearing bolts so that they are just slightly snug and then adjust the set screw to reposition it before fully tightening the nut (lower right photo).



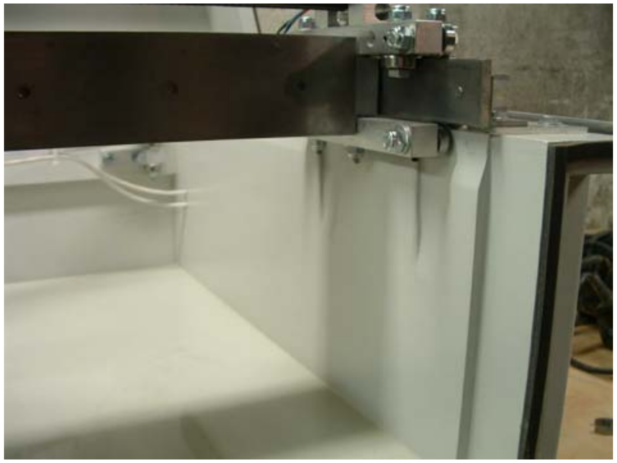
While adjusting these four bearings to get the Y rail parallel to the bed, occasionally check that the front face of the Y rail is relatively perpendicular to the bed (left photo). This does not need to be be exact, but the closer it is, the easier it will be to adjust the Z axis later. Of primary importance is getting the Y rail parallel to the bed.

Take your time with these adjustments and be patient. It may take multiple attempts to get the adjustment correct and will likely be frustrating and time consuming at first. Rest assured that you will develop a feel for adjusting the bearings and things will get quicker as you go.

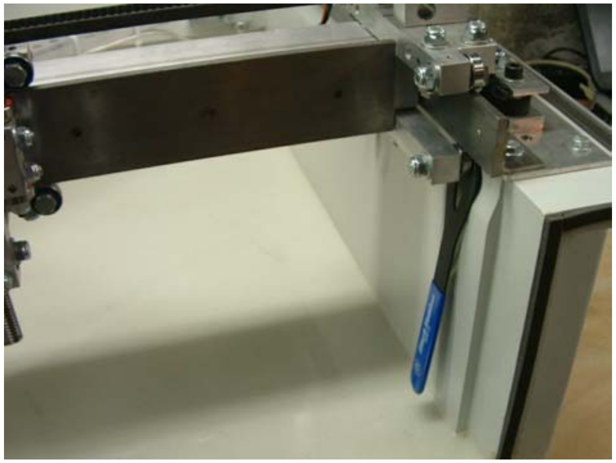


version 1.2

Once you are satisfied with the adjustment of the four bearings that ride along the tops of the rails, next adjust the four that ride along the lower edge. Move the gantry so that the bearings line up with the four depressions in the inner skins, as shown in the right photo. These are to allow clearance to get a wrench onto the heads of the bolts. However, as the bolt heads are thinner than normal , it will take a special wrench to fit onto them.



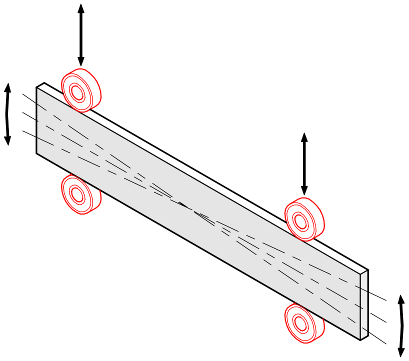
There are a couple of solutions to this. One is to simply grind down the head of a standard wrench so that it fits. If you do this, grind the wrench slowly to avoid overheating the metal. Cool it often by dipping it into water. Another solution is to use a ready made wrench. Many power tools have special wrenches to fit their arbors that are thin. I happened to have one for a router that was the required 1/2" size. Another option is to buy a bicycle cone wrench that is made for working on bicycle hubs (right photo). Buy one in a 13mm size. Note that this is a slightly loose fit on the 1/2" head (which is 12.7mm) but should work fine. These do not need to be excessively tightened, so no rounding should occur if you have the wrench squarely on the bolt head.



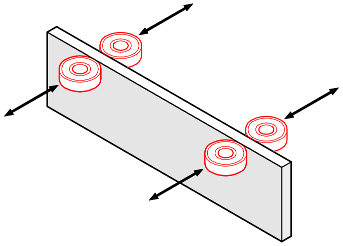
Adjust these four bearings up until they lightly touch the bottom edge of the rails. This also requires aquiring a feel for how tight against the rail they need to be. They need to be tight enough that there is no free play, but not so tight that they increase rolling resistance. A good test is that with the gantry stationary, you should still be able to grasp the bearing and turn it against the rail. It should slip against the rail when turned with some pressure. It should not slip very easily, but should not turn completely freely either.

I noticed that the first time I adjusted my machine I overtightened every set of bearings to the point where the stepper motors could not move the machine! I found it was better to go with an adjustment that seemed slightly too loose than too tight. It is also less difficult to later set an adjustment tighter than it is to make one looser.

version 1.2

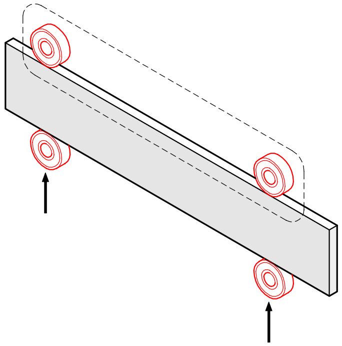


Most of the bearings on the machine are adjusted in sets that simultaneously touch opposing sides of a rail. This may either be across the width (left illustration), or across the thickness (right illustration). Keeping this in mind can help during adjustments as there are a couple of strategies that can be used to cause an adjustment to have the effect you need.

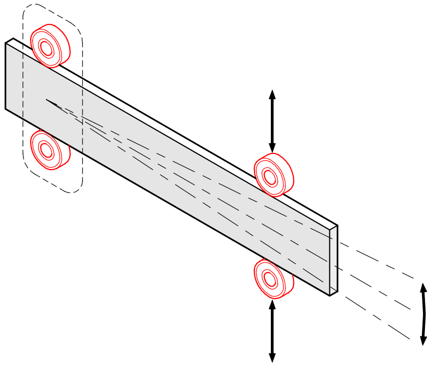


Adjusting two bearings along one surface (the top two bearings in the upper left illustration) can cause rotational shift or a parallel shift.

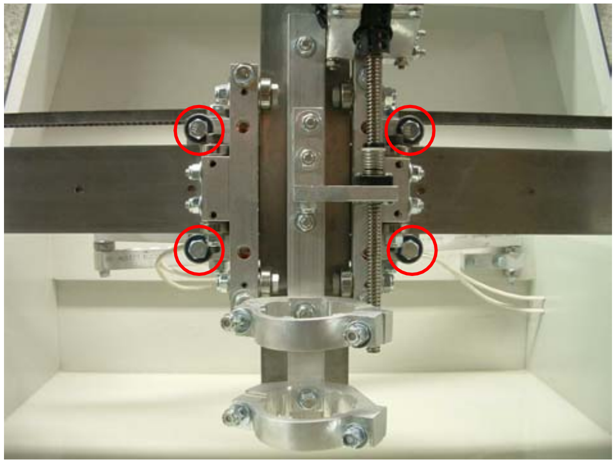
Once bearings along one surface are satisfactory, adjust in the opposing set (middle left illustration).



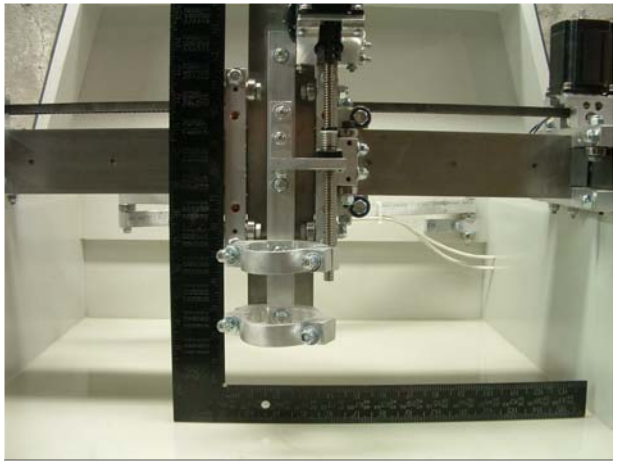
If all four bearings are making the desired amount of contact, a rotational shift can be accomplished by leaving two opposing ones alone, while adjusting the other two equal amounts in the same direction. (lower left illustration).



The next bearings to adjust will be the carriage bearings that ride along the Y rail. First we will adjust the four that contact the top and bottom edges (circled in the right photo).



While adjusting these four bearings, also try to get the carriage itself perpendicular to the bed, as shown in the photo to the right. This will make the Z axis alignment easier later.



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BENCHTOP CNC ROUTER PLANS

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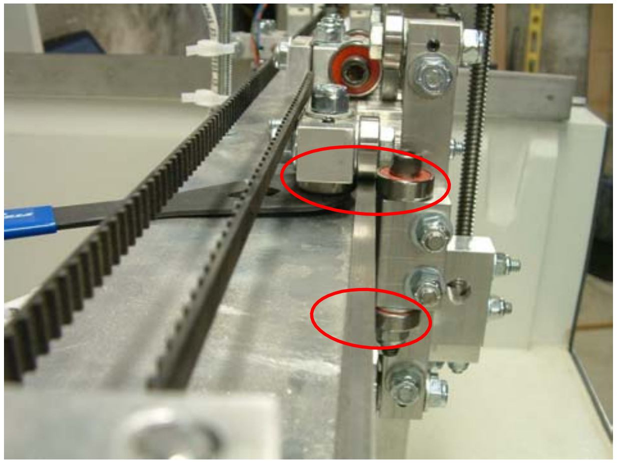
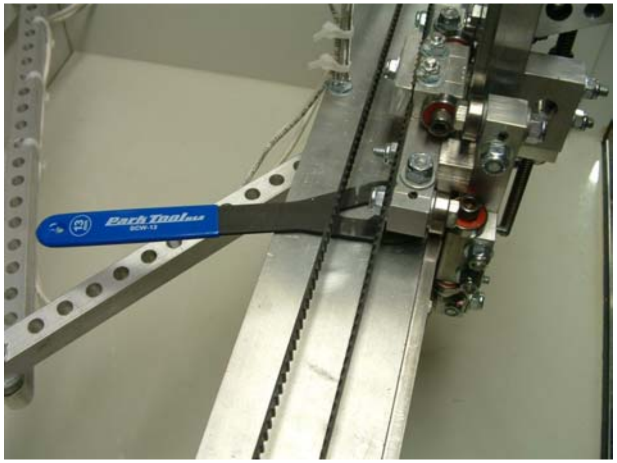
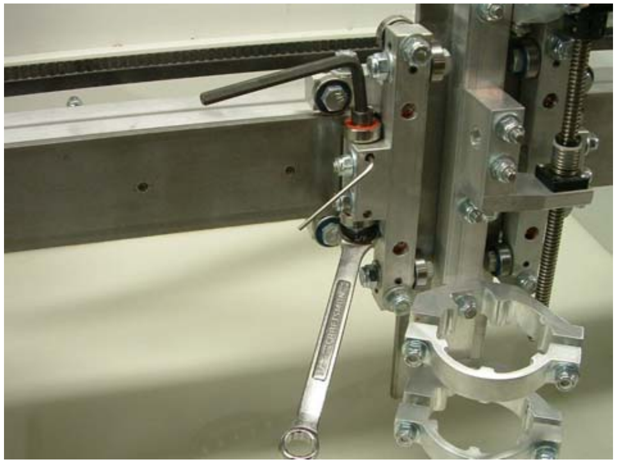
The Y axis bearings that ride along the front and rear faces of the rail are adjusted next. There are a total of eight bearings, that need to be adjusted as one group. Note that on the front ones, a single bolt secures two bearings at a time. Each bearing does have an individual set screw adjuster. I have found it easiest to adjust these double sets of bearings first (lower right photo), and then adjust the rear ones in to touch the rail (upper right photo).



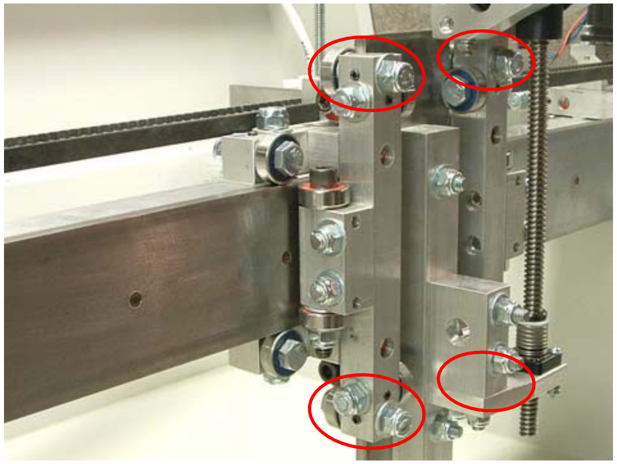
The rear bearings also use bolts with thinner heads for clearance, so the thin wrnech will be needed here too.

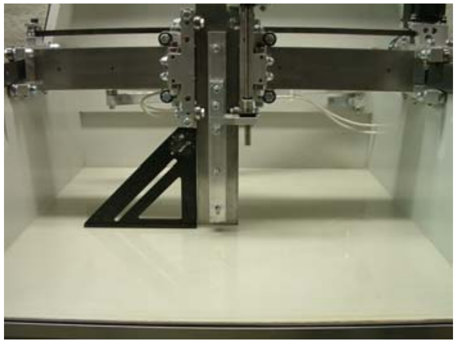




The next adjustment will be to the Z axis rail. This needs to be adjusted so that it is perpendicular to the machine bed in both side to side, and front/rear directions.

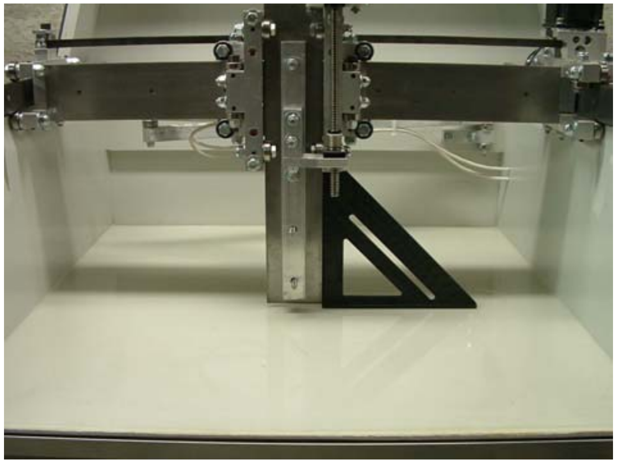
First adjust it side to side, using the four bearings circled to the right.





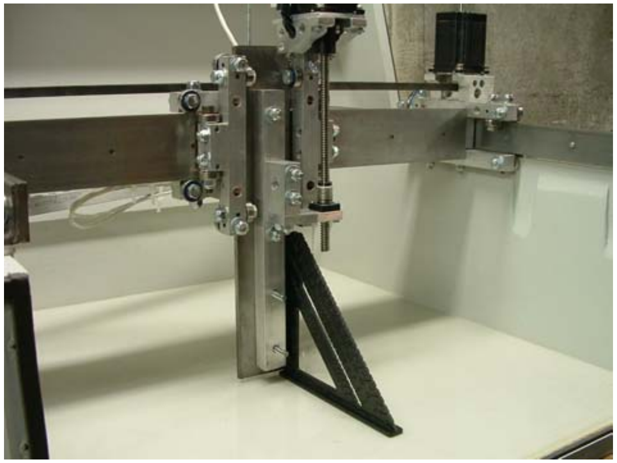
Jog the Z axis down so that it is nearly touhing the bed area. A triangle can now be used as a gauge. You may find it easier to do this with the router mounts removed for added working space.

When the Z rail is perpendicular to the bed, double check by flipping the triangle around and holding it up to the other side. If your triangle is not exactly a 90 degree angle, or the bed surface is uneven, then flipping the triangle to the other side will reveal the discrepancy, and that something is inaccurate.



Move the triangle to the front of the rail as shown in the photo to the right. Adjust the eight bearings that ride along the front/rear surfaces of the rail to get it perpendicular to the bed. These also have paired bearings, so use the technique that was used on the Y rail.

All three of the machine axes should now be adjusted and aligned.



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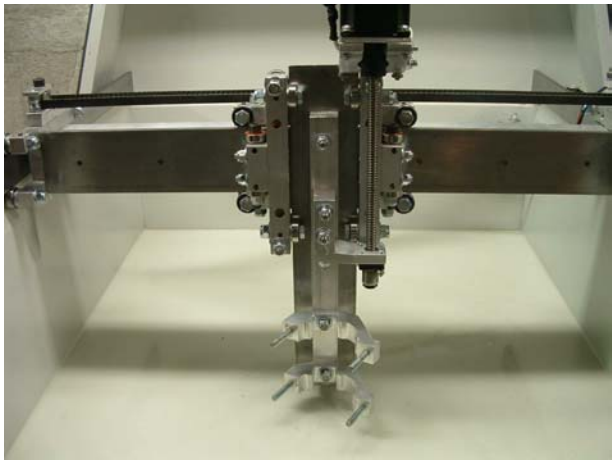
The one last adjustment is to the Z axis drive screw. There is no easy place to directly measure to find its proper positioning, so it will take some trial and error. Begin by jogging the Z axis to its lowest position. Tighten the #4-40 x 1" machine screws and nuts holding the anti-backlash nut so that they are snug enough to hold it in position, but it can still be repositioned with some slight force.

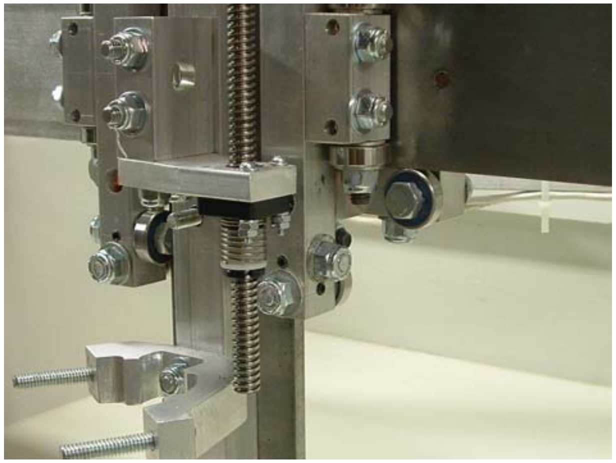
Standing in front of the machine, visually align the drive screw so that it is parallel to the Z axis rail.

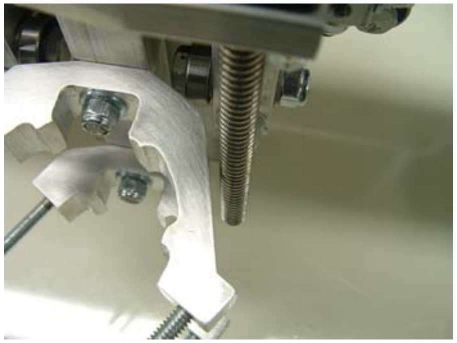
Move to the side of the machine and do the same in that direction.



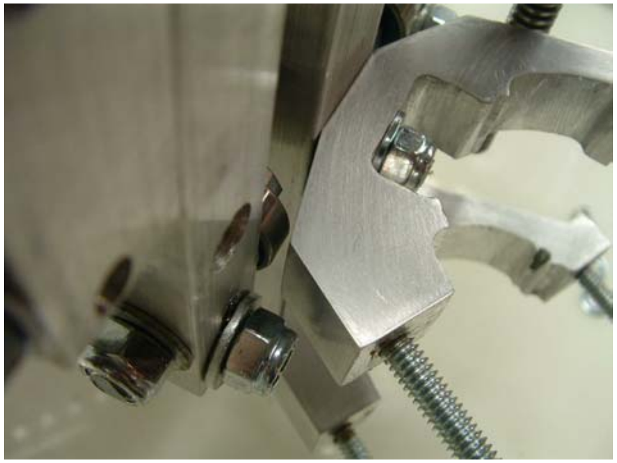
Jog the machine all the way to the top of its Z axis travel. It should not bind, and the sound from the stepper motors should stay consistent during the travel. Readjust as necessary. It will probably require jogging the Z axis up and down several times, readjusting each time, to finally get it correct.

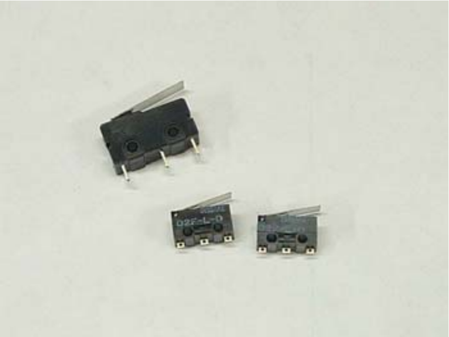
Once it is in a satisfactory position, tighten the machine screws/nuts fully. Make sure to either use threadlocking compound (the removable type), locknuts, or lockwashers. I used a combination of lockwashers and double nuts that are tightened against each other. These are highly vulerable to vibrating loose, and their small size does not allow excessive tightening without stripping threads.

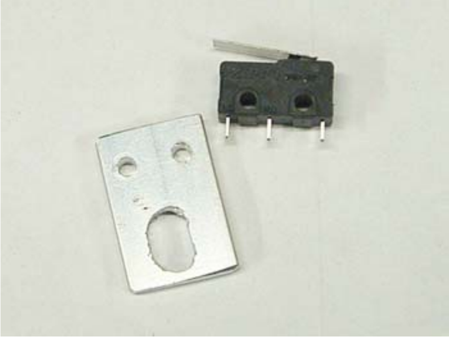


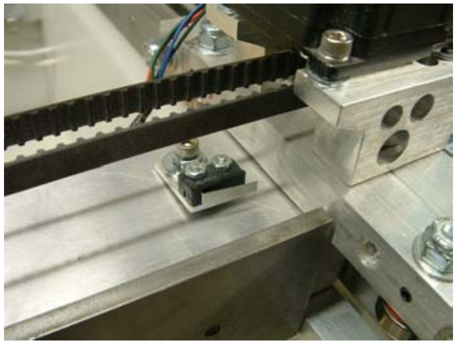


Make sure that there is plenty of clearance between the router mounts and the drive screw (left photo) and the Z axis bearings (right photo).









Use the triangle to align the clamping surfaces of the router mounts, and make sure they are perpendicular to the machine bed. Mount the router and run its cord along the same path as the stepper motor wiring.

The machine bed area should be equipped with a "spoilboard". This is a piece of MDF that can be easily replaced as it it wears (middle right photo). Any parts being cut on the machine that require the router bit penetrating all the way through the workpiece will obviously cut into the surface below, so this inexpensive replaceable surface is used. You can also directly screw a workpiece down to it, or screw a clamping arrangement down to it.

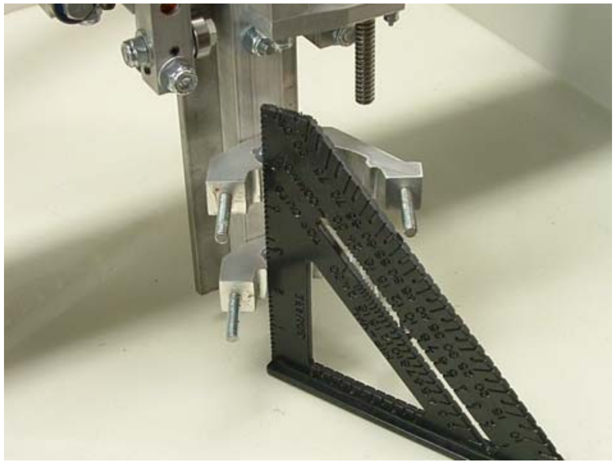
I used a piece of 3/4" MDF, about 16" wide, and the full front to rear dimension. I secured it with 3 screws at each end. Drill clearance holes through the MDF for the screws. Make sure these screws are in a position that is beyond the cutting area of the router, so that the bit cannot hit them.

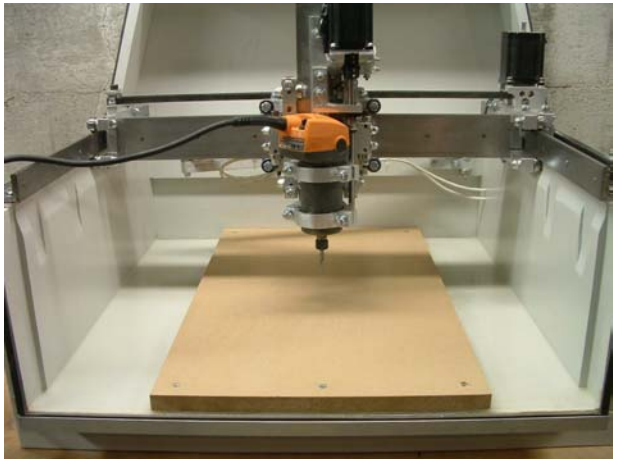
When screwing a workpiece or clamps to the spoilboard, it is good practice to use brass screws. They are softer than steel so they will cause less damage to a turing router bit if you accidentally hit one. It can also prevent the bit from shattering, which is obviously a dangerous situation. Drill pilot holes into the spoilboard before screwing anything to it, especially when using the brass screws.

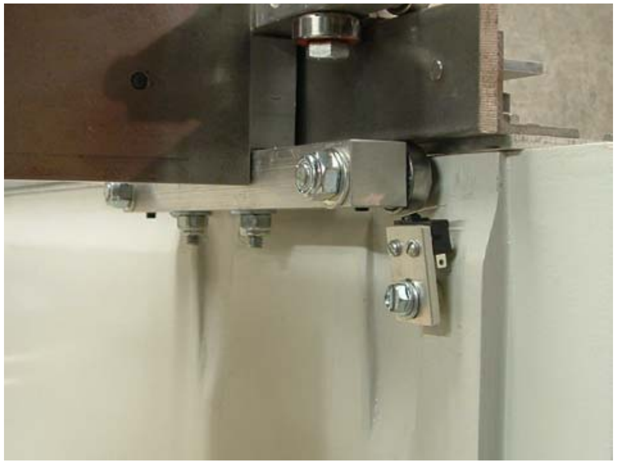
Do any final routing of wiring and the machine is ready for use. This includes the wiring of limit switches. Do not use the machine without limit switches. They are not optional. Due to the variety of limit switch types and sizes (upper left photo), you will need to fabricate mounts of some sort for your particular variety. There should be a total of 6 switches, one at each end of the travel for each axis.

I fabricated small brackets from 1/8" x 1" aluminum flat stock as seen in the middle left photo. I mounted them so that a bearing wil "roll" onto them at the end of each axis. The lower left photo shows the mounted position on the right side of the gantry. Drill and tap a #10-32 hole to mount the bracket. The lower right photo shows the front X axis switch and its relationship to the bearing that trips it.

If you are using the switches only as emergency limit switches, then they can all be wired in series, using only one parallel port input. To use them as homing switches as well, each axis requires separate wiring and its own parallel port input.







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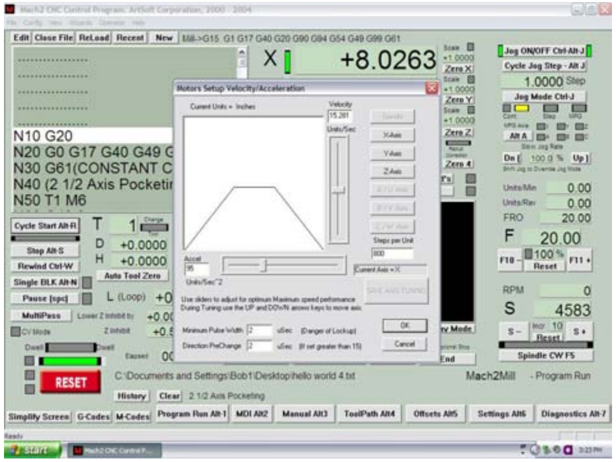
Jog the machine axes to test that the limit switches are functioning correctly. Also test that the emergency stop button is functioning.

Make any final configurations to the controller software. I you have not already, you will need to define the number of motor steps per inch. The belt drive on the X and Y axes provide 2" of movement for every revolution of the stepper motor. Doing a little math, this works out to 100 motor steps per inch of travel, if using a typical 200 steps/revolution stepper motor. If you are using a microstepping drive, you need to multiply this number by the microstepping factor. For instance, the Xylotex board I am using is configured for 1/8 microstepping, or 8x. So multiplying 8 x 100 = 800 steps per inch of travel This figure can be seen entered in the window to the right.



```
N10 G20
N20 G0 G17 G40 G49 G
N30 G61(CONSTANT C
N40 (2 1/2 Axis Pocketi
N50 T1 M6
```

Velocity: 15.281 Units/Sec

Steps per Unit: 800

Accel: 95 Units/Sec^2

Use sliders to adjust for optimum Maximum speed performance
During Tuning use the UP and DOWN arrows keys to move axis.

Minimum Pulse Width: 2 uSec (Danger of Lockup)

Direction PreChange: 2 uSec (If set greater than 15)

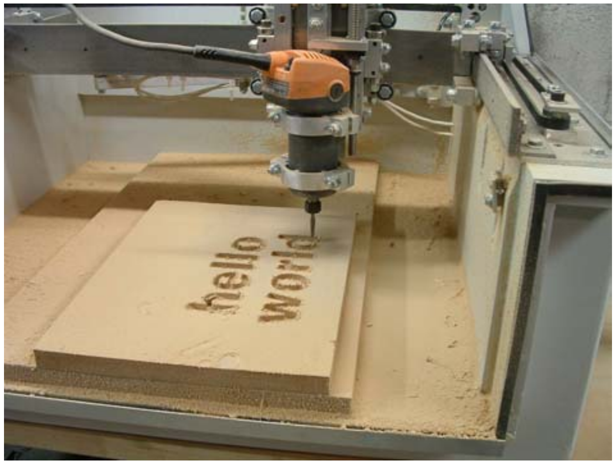
T 1 · D +0.0000 · H +0.0000

Units/Min 0.00 · Units/Rev 0.00 · FRO 20.00 · F 20.00 · 100 % · RPM 0 · S 4583

C:\Documents and Settings\Bob1\Desktop\hello world 4.txt

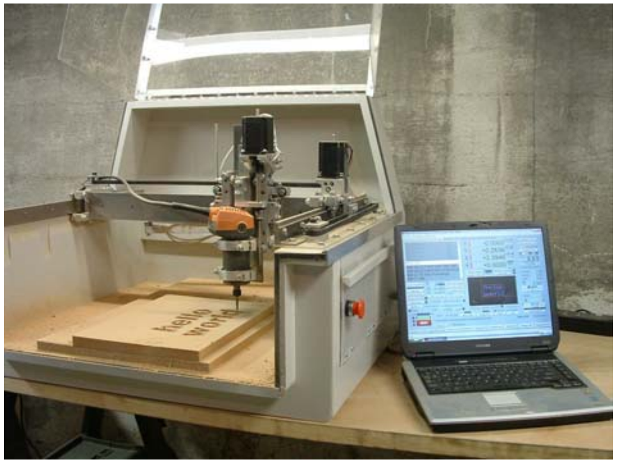
2 1/2 Axis Pocketing

The Z axis drive screw is 10 threads/inch, which means 10 revolutions of the motor moves that axis one inch. Multiplying this times the 200 motor steps per revolution equals 2000 steps per inch. If using an 8x microstepping drive, this would result in 16,000 steps per inch.



Note that these are ideal theoretical numbers. Any inaccuracies in the belts or drive screw are not accounted for. It is a good idea to use the machine to cut a part to a desired size, and then accurately measure it with digital calipers or a micrometer to see how close it is. If it is off, corrections can be made to the steps/inch value to compensate for the deviation. As the belts do have some small amount of stretch to them, it is likely that the X and Y axes will require some small adjustment to make them 100% accurate.

Ok, time to cut something! If you haven't already, it is time to figure out how to draw something and go through the process of using CAM software to turn that into G-code.



As soon as you start cutting, you will see the benefit of having a covered machine. As you can see in the photo to the right, after cutting only one trial piece, the machine is covered in dust. Clean the machine between uses, especially any accumulation on the rail surfaces.

This concludes the building of the machine, and I wish you many enjoyable hours of putting it to use. Get creative!

-Bob Pavlik
2010
momus.design@gmail.com

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SUPPLIERS

Metals

Online Metals
1138 West Ewing
Seattle, WA 98119
800_704_2157
http://www.onlinemetals.com/
sales@onlinemetals.com

Speedy Metals
locations in Wisconsin, Michigan, Texas
http://www.speedymetals.com/

Metals Depot
4200 Revilo Road
Winchester, KY 40391
http://www.metalsdepot.com/

Power Transmission

Dumpster CNC
http://dumpstercnc.com/
dumpster95@yahoo.com
-anti-backlash nuts
-motor couplings

McMaster-Carr
http://www.mcmaster.com/
-precision acme threaded rod

Stock Drive Products
http://www.sdp_si.com/
-drive belt
-timing pulleys

Bearings

Ebay vendor:
user id: irvineman
store name: VXB Bearings Skateboard and Slotcar

Stepper Motor Drives

Xylotex
Xylotex, Inc.
2626 Lavery Court #307
Newbury Park, CA 91320
http://www.xylotex.com/
support@xylotex.com
http://groups.yahoo.com/group/Xylotex/

GeckoDrive Motor Controls
14662 Franklin Ave.
Suite E
Tustin, CA 92780
http://www.geckodrive.com/
http://groups.yahoo.com/

Software

ArtSoft
Newfangled Solutions LLC
443 Lovejoy Shores Dr.
Fayette, ME 04349
http://www.machsupport.com/
Mach3 CNC controller

MecSoft
18019 Sky Park Circle
Ste: KL
Irvine CA 92614
http://www.mecsoft.com/
FreeMill (free!)
Visual Mill
RhinoCam

Multiple Items

Ebay vendor:
user id: carolbrent
store name: HUBBARD CNC INC

Hardware

Bolt Depot
www.boltdepot.com
-hardware

Ebay vendor:
user id: 5137jones
store name: BOLT IT UP
-hardware

Epoxy

Jamestown Distributors
17 Peckham Drive
Bristol, RI 02809
http://www.jamestowndistributors.com/
-MAS low viscosity epoxy

Ebay vendor:
user id: polymerproducts
store name: Polymer Products
-low viscosity resin

NOTE:

I have no affiliation with any of these vendors. They are mostly companies or individuals that I have purchased from and have received outstanding customer service. There are many other suppliers and their exclusion here in no way indicates that they are any less worthy of an endorsement.

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